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NIST Technical Note 1263

Guidelines for Implementing the New Representations of the Volt and Ohm Effective January 1, 1990

Norman B. Belecki, Ronald F. Dziuba, Bruce F. Field, and Barry N. Taylor

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- Fracture and Deformation[3]
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[1]Headquarters and Laboratories at Gaithersburg, MD, unless otherwise noted; mailing address Gaithersburg, MD 20899.
[2]Some divisions within the center are located at Boulder, CO 80303.
[3] Located at Boulder, CO, with some elements at Gaithersburg, MD.

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NOTE: As of 23 August 1988, the National Bureau of Standards (NBS) became the National Institute of Standards and Technology (NIST) when President Reagan signed into law the Omnibus Trade and Competitiveness Act.

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Abstract

This document provides general guidelines and detailed instructions on how to bring laboratory reference standards of voltage and resistance and related instrumentation into conformity with newly established and internationally adopted representations of the volt and ohm. Based on the Josephson and quantum Hall effects, respectively, the new representations are to come into effect worldwide starting on January 1, 1990. Their implementation in the U.S. will result in increases in the values of the national volt and ohm representations maintained at the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards or NBS) of 9.264 parts per million (ppm) and 1.69 ppm, respectively. The resulting increase in the value of the U.S. representation of the ampere will be 7.57 ppm and in the U.S. electrical representation of the watt, 16.84 ppm. Also discussed are the effects on electrical standards of the January 1, 1990, replacement of the International Practical Temperature Scale of 1968 by the International Temperature Scale of 1990, and of the January 1, 1990, approximate 0.14 ppm decrease in the U.S. representation of the farad.

Scope

This document and the adjustments described in it apply primarily to standards, instruments, and test equipment used for measurements of voltage or for voltage calibrations at the 100 part per million (ppm) level of uncertainty or better, and to standards and instruments used for resistance measurements or calibrations at the 20 ppm level of uncertainty or better. Other types of electrical measurements possibly affected are those of power and energy at the 170 ppm level of uncertainty or better, alternating current and voltage measurements inasmuch as they are based on dc standards (100 ppm or better), and capacitance measurements at the highest levels of accuracy (2 ppm or better). Instruments and standards having uncertainty tolerances greater than these levels will not be affected.

Executive Summary

By international agreement, starting on January 1, 1990, the national standards laboratories of most major industrialized countries will put into place new representations of the volt and ohm based, respectively, on the Josephson and quantum Hall effects and which are highly consistent with the International System of Units or SI. Here, the volt is the SI unit of electromotive force and electric potential difference. In the past, 'legal volt', 'as-maintained volt', 'national unit of voltage', 'laboratory unit of voltage', and other similar terms were commonly used to indicate a 'practical unit' for expressing measurement results. To avoid misunderstanding, in these *Guidelines* the word *unit* is not used in this context; the expression *representation of the volt* and variations thereof are used in its place. The situation for the ohm and resistance is strictly analogous.

Also by international agreement, starting on January 1, 1990, the national standards laboratories of countries that do not have Josephson and quantum Hall effect reference standards are requested to maintain their own national representations of the volt and ohm so as to be consistent with the new internationally agreed-upon representations. This consistency can be achieved through periodic comparisons with a laboratory that does have Josephson and quantum Hall effect standards. As a consequence, starting on January 1, 1990, the previous significant differences among the values of some national volt representations, among the values of many national ohm representations, and the differences between the values of most national volt and ohm representations and the SI should no longer exist.

Implementation of the new volt and ohm representations in the U.S. requires that on January 1, 1990, the value of the present national volt representation maintained by the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards or NBS) be increased by 9.264 parts per million (ppm) and that the value (on this date) of the national ohm representation be increased by 1.69 ppm. The resulting increases in the present national representation of the ampere and in the present national electrical representation of the watt will be 7.57 ppm and 16.84 ppm, respectively.

The required January 1, 1990, changes in the U.S. volt and ohm representations are sufficiently large that literally thousands of electrical reference standards, electrical measuring instruments, and electronic systems throughout the Nation will have to be adjusted in order to bring them into conformity with the new representations. (Similar adjustments will have to be made in other countries as well.) Examples of such equipment are groups of standard cells in thermoregulated enclosures and oil baths; solid-state voltage references and standards; wire-wound and metal-film standard and precision resistors; high precision digital voltmeters, multimeters, programmable sources, calibrators, and standard watthour meters; automatic test equipment or ATE; and avionics systems.

The purpose of this document is to provide general guidelines, detailed instructions, and helpful background information for those individuals and organizations that must deal with or are in some way affected by the January 1, 1990, changes in the U.S. volt and ohm representations. These include metrologists, standards and calibration laboratories and their personnel, equipment managers, quality assurance personnel, instrument manufacturers and rental companies, engineers involved in manufacturing, production, and testing, ATE users and designers, and those involved with procedures and software.

Because the 9.264 ppm increase in the U.S. volt representation is 19% of a 50 ppm tolerance, voltage standards and related instrumentation are especially affected. Inasmuch as these *Guidelines* give technical advice, point out potential problems, and identify precautions to be taken, they are essential reading for those individuals who are in any way involved with or are responsible for such hardware. To assist NIST in the preparation of the *Guidelines*, National Confer-

ence of Standards Laboratory Ad Hoc Committee 91.4 "Changes in the Volt and Ohm" was formed with broad representation from the electrical metrology community. The committee members helped to determine its contents, provided useful comments, and served as a knowledgeable sounding board for ideas.

Also, starting on January 1, 1990, the International Temperature Scale of 1990 (ITS–90) will supersede the International Practical Temperature Scale of 1968 (IPTS–68). The new temperature scale is much more consistent with thermodynamic temperature than is IPTS–68, which has been found to deviate significantly from thermodynamic temperature in certain temperature regions. The introduction of ITS–90 in place of IPTS–68 will affect electrical reference standards such as standard cells and resistors since they are assigned values at particular temperatures. These *Guidelines* give detailed instructions on how to deal with changes in electrical standards introduced by ITS-90.

Moreover, on January 1, 1990, the U.S. representation of the farad will be decreased by about 0.14 ppm to bring it into better agreement with the farad as defined in the SI. The effect of this change is also discussed.

An important consequence of adjusting standards and instruments throughout the world so that they conform with the new internationally adopted representations of the volt and ohm based on the Josephson and quantum Hall effects is improved uniformity of electrical measurements worldwide and their consistency with the SI. The resulting significant benefits to commerce, industry, and science throughout the world are expected to far outweigh the costs of making the adjustments.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

Guidelines for Implementing the New Representations of the Volt and Ohm Effective January 1, 1990

Norman B. Belecki, Ronald F. Dziuba, Bruce F. Field, and Barry N. Taylor

1. Introduction

By international agreement, starting on January 1, 1990, new practical representations of the volt and ohm based on the Josephson and quantum Hall effects, respectively, will come into effect worldwide. It is the principal purpose of this document to provide detailed instructions on how to bring laboratory reference standards of voltage and resistance and related instrumentation into conformity with the new representations. This introductory portion of the *Guidelines* contains background information which should help the reader better understand the more practical sections. However, it is highly abbreviated since such information is available in a number of publications[1–8].[1] For the convenience of the reader, those articles that are likely to be of most use (refs. [1, 3, 4, 5]) are reprinted in Appendix 3.

1.1 NCSL Ad Hoc Committee 91.4

This document would not have been possible without the active assistance of the members of National Conference of Standards Laboratories (NCSL) Ad Hoc Committee 91.4 "Changes in the Volt and Ohm" (the Committee members and their affiliations are listed in Appendix 1). Drawn from a large number of organizations spanning the range from DoD (Department of Defense) standards laboratories to manufacturers of high precision electrical measuring instruments, their varied backgrounds helped to ensure that the needs of all segments of the U.S. electrical metrology community were addressed by these *Guidelines*. Through dedicated Committee meeting attendance and participation as well as by correspondence, they provided much valuable information and many critical comments. Indeed, Appendix 2 directly reflects the views of Committee members regarding management and logistics issues. The Committee especially served as an extremely knowledgeable sounding board for ideas proposed by the members from NIST (formerly the National Bureau of Standards or NBS). The authors thank all of the members of 91.4 for their many contributions to this document but, of course, take full responsibility for any omissions or errors.

1.2 The SI Units of Electromotive Force and Resistance and Their Representations

The International System of Units [9], abbreviated SI, serves as a basis for the promotion of long-term, worldwide uniformity of measurements. In the SI, the unit of electromotive force or emf (symbol E) and electric potential difference (U) is the volt (V). The unit of resistance (R) is the ohm (Ω). In practice, the volt and ohm, which occasionally may be referred to in the literature as the absolute volt and ohm, may be realized in a number of ways. These include comparing electrical power with mechanical power (for the volt) using a force balance [10], and resistance with impedance (for the ohm) using a calculable capacitor [11,12].

However, commercial, industrial, and scientific requirements for the long-term repeatability and worldwide consistency of measurements of emf/electric potential difference and resistance often exceed the accuracy with which the SI units for such measurements, the volt and the ohm, can be readily realized. To meet these severe demands, it has become necessary to establish *representations* of the volt and ohm that have superior long-term reproducibility and constancy compared with the present direct realizations of the volt and ohm themselves.

Since the phrase *representation of the volt* may be unfamiliar to some readers, it requires explanation. In the past, 'legal volt', 'as-maintained volt', 'national unit of voltage', 'laboratory unit of voltage', 'practical realization of the volt', and other similar terms were commonly used to indicate a 'practical unit' for expressing measurement results. However, to avoid possible misunderstanding, it is best not to use the word *unit* in this context. The only unit of emf and electric potential difference in the SI is, of course, the volt. In these *Guidelines*, the expression *representation*

[1] References are listed on page 28.

of the volt and variations thereof are used in its place. The situation for the ohm and resistance is strictly analogous.

Historically, laboratory volt representations have been based on electrochemical standard cells. However, starting in the early 1970's, it became possible for national standards laboratories to base their volt representation on the Josephson effect in order to avoid the well-known problems associated with the emf's of standard cells, for example, their variation with time (i.e., drift), severe dependence upon temperature, and occasional unpredictable abrupt changes.

On the other hand, most national standards laboratories have continued to base their ohm representation on the mean resistance of a particular group of wire-wound standard resistors. Because such artifact standards age, the various national ohm representations differ significantly from each other and the SI ohm, and some are drifting excessively. Electrical metrologists therefore welcomed Klaus von Klitzing's 1980 discovery of the quantum Hall effect (QHE) since it promised to provide a method for basing a representation of the ohm on invariant fundamental constants in direct analogy with the Josephson effect. The QHE clearly had the potential of eliminating in a relatively straightforward way the problems of nonuniformity of national ohm representations, their variation in time, and their inconsistency with the SI.

1.3 Josephson and Quantum Hall Effect Reference Standards of Voltage and Resistance

The Josephson effect is characteristic of weakly coupled superconductors when cooled below their transition temperatures. An example is two thin films of superconducting lead separated by an approximately 1 nm-thick thermally grown oxide layer. When such a Josephson junction is irradiated with microwave radiation of frequency f, its current vs voltage curve exhibits steps at highly precise quantized Josephson voltages U_J. The voltage of the nth step $U_J(n)$, n an integer, is related to the frequency of the radiation by

$$U_J(n) = nf/K_J, \qquad (1.1)$$

where K_J, now termed the Josephson constant, is a universal quantity independent of experimental variables, such as type of superconductor and irradiation frequency, to very high precision. (It follows from eq. (1.1) that K_J is the frequency-to-voltage quotient of the $n = 1$ step.) Indeed, theory and experiment indicate that K_J is equal to the invariant quotient of fundamental constants $2e/h$, where e is the elementary charge and h is the Planck constant. Numerically, K_J is about 483 598 GHz/V. Because quantized Josephson voltages depend only upon a readily measured frequency and invariant fundamental constants of nature, a volt representation based on the Josephson effect has none of the problems characteristic of standard cells indicated above.

The QHE is characteristic of certain high-mobility semiconductor devices of standard Hall-bar geometry when placed in a large applied magnetic field and cooled to a temperature near one kelvin. For a fixed current I through a QHE device there are regions in the curve of Hall voltage vs gate voltage, or of Hall voltage vs magnetic field depending upon the device, where the Hall voltage U_H remains constant as the gate voltage or magnetic field is varied. These regions of constant Hall voltage are termed Hall plateaus. Under the proper experimental conditions, the quantized Hall resistance of the ith plateau $R_H(i)$, defined as the quotient of the Hall voltage of the ith plateau to the current I, is given by

$$R_H(i) = U_H(i)/I = R_K/i, \qquad (1.2)$$

where i is an integer and R_K is now termed the von Klitzing constant after the discoverer of the QHE. (It follows from eq. (1.2) that R_K is equal to the resistance of the $i = 1$ plateau.) The von Klitzing constant has been shown to be a universal quantity independent of experimental variables, such as type of QHE device and plateau number, to high precision. Indeed, theory and experiment indicate that R_K is equal to the invariant quotient of fundamental constants h/e^2. Numerically, R_K is about 25 813 Ω.

1.4 The Internationally Adopted Values of the Josephson and von Klitzing Constants

At its October 1988 meeting [1,3], the International Committee of Weights and Measures (CIPM) recommended that all national standards laboratories that base their representation of the volt on the Josephson effect adopt the same conventional value of K_J, namely,

$$K_{J\text{-}90} = 483\,597.9 \text{ GHz/V} \qquad (1.3)$$

exactly, where the subscript 90 indicates that this value is to come into effect starting on January 1, 1990, and

not before. The CIPM also stated its belief that an ideal volt representation based on the Josephson effect and K_{J-90} will be consistent with the SI volt to within a one-standard-deviation (1σ) assigned uncertainty of 0.4 parts per million (ppm). Similarly, the CIPM recommended that all national standards laboratories that choose to base their representation of the ohm on the QHE use the same conventional value of the von Klitzing constant, namely,

$$R_{K-90} = 25\,812.807\ \Omega; \tag{1.4}$$

and stated its belief that an ideal ohm representation based on the QHE and R_{K-90} will be consistent with the SI ohm to within an assigned 1σ uncertainty of 0.2 ppm.

It should be recognized that the definitions of the SI volt and ohm are not being changed; rather, more accurate representations of them have been made possible by improvements in measurement science.

1.5 Symbols for the Old and New U.S. Volt and Ohm Representations

The U.S. volt representation maintained at NIST has been based on the Josephson effect since July 1, 1972, and the U.S. ohm representation has been based on the mean resistance of groups of standard resistors since January 1, 1948.

For the purpose of explaining how to bring standards and instruments calibrated in terms of these pre-January 1, 1990, representations into conformity with the new, post January 1, 1990, representations, we shall use the following symbols defined as indicated:

V(NBS–72) — The U.S. representation of the volt based on the Josephson effect maintained at NBS/NIST during the period July 1, 1972, through December 31, 1989, using K_J = 483 593.420 GHz/V(NBS-72) exactly as the value of the Josephson constant [13]. (NIST was the National Bureau of Standards or NBS prior to August 23, 1988.)

V(NIST–90) — The U.S. representation of the volt based on the Josephson effect to be maintained at NIST starting January 1, 1990, using the new internationally agreed upon or conventional value of the Josephson constant, K_{J-90} = 483 597.9 GHz/V exactly. Since K_{J-90} exceeds the previous value of K_J used by NBS/NIST by 9.264 ppm, V(NIST–90) exceeds V(NBS–72) by this amount.

Ω(NBS–48)$_t$ — The U.S. representation of the ohm based on the mean resistance of groups of standard one-ohm resistors maintained at NBS/NIST during the period January 1, 1948, through December 31, 1989. The subscript *t* indicates that this ohm representation is time dependent and thus has a unique value only at the time *t*.

Ω(NIST–90) — The U.S. representation of the ohm based on the quantum Hall effect to be maintained at NIST starting January 1, 1990, using the internationally agreed-upon or conventional value of the von Klitzing constant, R_{K-90} = 25 812.807 Ω exactly. From quantized Hall resistance measurements it is calculated that Ω(NIST-90) will exceed Ω(NBS–48)$_{01/01/90}$ by 1.69 ppm.

It must be emphasized that these symbols will be used only in this document and for the explanatory purpose given near the start of this section. When reporting the results of NIST calibrations of client voltage and resistance standards in terms of the new 1990 volt and ohm representations (starting January 1, 1990), NIST will follow the recommendation of the Consultative Committee on Electricity (CCE), affirmed by the CIPM, and not use any distinguishing symbols on either unit symbols or quantity symbols [1, 3, 6]. That is, calibration results will be expressed in terms of V and Ω, not V(NIST–90) and Ω(NIST–90); see sec. 5 for a detailed discussion.

The January 1, 1990, increases of 9.264 ppm and 1.69 ppm in the values of the U.S. volt and ohm representations, respectively, will require the adjustment of literally thousands of electrical reference standards, electrical measuring instruments, and electronic systems throughout the U.S. in order to bring them into conformity with the new 1990 volt and ohm representations. (Similar adjustments will have to made in other countries as well.) Examples of the type of equipment affected are groups of standard cells in themoregulated enclosures and oil baths; solid-state voltage references and standards; wire-wound and metal-film standard and precision resistors; high precision digital voltmeters, multimeters, programmable sources, calibrators, and reference standard watthour meters; automatic test equipment or ATE; and avionics systems.

It is the principal purpose of these *Guidelines*, especially the remaining sections, to help those individuals and organizations that must deal with such equipment to accommodate to the new representations

of the volt and ohm in as efficient a manner as possible. Indeed, twenty years ago when there were far fewer voltage standards and related instruments and systems in existence for which 10 ppm was at all significant, the January 1, 1969, decrease of 8.4 ppm in the U.S. volt representation caused considerable difficulty and many individuals dealt with it incorrectly. These *Guidelines* are a direct result of the 1969 experience when no such detailed document was available.

2. General Guidelines

To repeat, on January 1, 1990, the volt and ohm representations in the United States will change. This will immediately create an incompatibility between your volt and ohm standards and those of NIST and the rest of the world *unless you act to bring yourself into compliance with the changes*. The changes are +9.264 ppm and +1.69 ppm for the volt and ohm representations, respectively, or

$$V(\text{NIST–90}) = 1.000\,009\,264\ V(\text{NBS–72})$$

and

$$\Omega(\text{NIST–90}) = 1.000\,001\,69\ \Omega(\text{NBS–48})_{01/01/90}.$$

Accordingly, those receiving calibration reports from NIST dated January 1, 1990, or later will find the reported values for voltage and resistance standards to be 9.264 ppm and 1.69 ppm smaller, respectively, than they would have been had no change taken place.

Because of the relatively small size of the changes, most instruments will not be affected; however, high accuracy standards and test equipment will be. The following section gives recommendations about how to determine what class of instruments should be adjusted.

2.1 Identifying Standards and Instruments Affected

As noted above, the National Conference of Standards Laboratories (NCSL), in cooperation with NIST, formed Ad Hoc Committee 91.4, "Changes in the Volt and Ohm," to help the metrology community come into compliance with the new volt and ohm representations. The committee has wide-spread technical and management representation from industry and government and this document reflects the thinking of its membership.

The conservative rule recommended by NCSL Ad Hoc Committee 91.4 for use in determining the circumstances for which adjustments to test equipment and instrumentation should be made is:

- if any required measurement uncertainty is less than or equal to five times the magnitude of the change, adjustment of the instrument should be made as soon as practical on or after January 1, 1990;
- if required measurement uncertainties are between five and ten times the magnitude of the change, this constitutes a "gray" area and the situation must be assessed on a case-by-case basis; and
- if all required measurement uncertainties are greater than ten times the magnitude of the change, no adjustment need be made.

However, since standards are the beginning of the calibration chain, the recommendation regarding their adjustment is more conservative. The values of *all voltage standards* having accuracies of 100 ppm or better should be adjusted to bring them into compliance with the changes. For resistance, the values of *all* standards with accuracies of 20 ppm or better should be adjusted. The adjusted values should be used beginning January 1, 1990, the date that the changes legally take effect. A delay in implementing the changes, even for secondary standards, creates the possibility that instruments recalibrated after the date of the changes might unintentionally be calibrated in terms of $V(\text{NBS–72})$ or $\Omega(\text{NBS–48})_t$.

Table I describes the application of the Ad Hoc Committee rule to manufacturers' specifications for instruments and test equipment. In each case, the magnitude of the change was rounded up to the next highest whole number (in ppm).

It follows from this rule that the instrument accuracy required and its ratio to the magnitude of the change must be determined in order to decide if the instrument should be adjusted. The manufacturer's specifications may be used for this purpose. They generally give instrument accuracies to be expected for several different time intervals; for example, digi-

TABLE I
MANUFACTURERS' SPECIFIED ACCURACIES (MSA)
IN PPM

	Volt	Ohm
Must Adjust	MSA ≤ 50	MSA ≤ 10
"Gray" Area	50 < MSA < 100	10 < MSA < 20
Forget It	MSA ≥ 100	MSA ≥ 20

tal voltmeter accuracies are commonly given for 24 hours, three months, and one year. Typically, one set of specified accuracies is chosen based on the desired recalibration interval. The 91.4 recommendation is to use this chosen accuracy to make the adjustment decision for normal use situations, but the manufacturer's 24-hour accuracy specification should be considered for use in situations of special criticality, when the test equipment is frequently removed for other uses under uncontrolled circumstances, or when extremely conservative practice is desired.

Since 9.264 ppm is significant relative to accuracies of 50 ppm or better, all voltage instrumentation normally calibrated to this level of accuracy should be adjusted as soon as practical on or after January 1, 1990. However, it is clear that a change of 9.264 ppm will not have a significant effect on the results of measurements made using an instrument whose accuracy specifications are at the 100 ppm level or worse. No effort should be made to adjust or recalibrate such instrumentation other than that normally made, i.e., the change can be ignored.

Instruments and test equipment whose calibrated accuracy for voltage measurements lies between 50 and 100 ppm fall into a "gray" area. The decision of whether to adjust immediately or wait until the instrument is due for recalibration must be made on a case-by-case basis depending on the use to which the particular instrument or device is put, its interval between recalibrations, and particularly on the criticality of the measurements for which it is used.

The increase in the value of the ohm representation of 1.69 ppm is much smaller. Therefore, in the case of multimeters and calibrators with resistance capabilities, those with calibration specifications of 20 ppm or greater can safely be ignored (i.e., not adjusted until their regular calibration due date); those with specifications of 10 ppm or better should be adjusted as soon as practical; and the range in between again constitutes a "gray" area where each case should be individually decided. The population of instrumentation requiring adjustments for resistance measurements is extremely small.

The increase in the ampere representation will be 7.57 ppm. There are no standards for current *per se;* voltage and resistance standards are used to measure currents. A limited number of instruments are capable of current measurements at the 80 ppm level. If, however, adjustments must be made to a digital multimeter or a calibrator, the manufacturer's procedures should be followed.

The National Conference of Standards Laboratories, in cooperation with U.S. manufacturers of test equipment, is compiling lists of model numbers of test equipment which should definitely be adjusted and which should be considered for adjustment. These lists will be obtainable by writing:

The National Conference of Standards
Laboratories
1800 30th Street, Suite 305B
Boulder, CO 80301
Telephone (303) 440-3339.

The lists will also be made available through GIDEP, the Government Industry Data Exchange Program. For further information write to:

Government - Industry Data Exchange Program
GIDEP Operations Center
Corona, CA 91720
Telephone (714) 736-4677.

2.2 Do's and Don'ts

2.2.1 Full recalibrations may not be necessary

Keep in mind that *full recalibrations are probably not necessary.* In a full recalibration, a large selection of values over all ranges and functions is typically measured to determine if the instrument meets specifications, and to adjust it if necessary. In the instruments which will be most affected by the changes — dc voltage calibrators, high-resolution programmable voltage sources, precision digital multimeters, and a few of the most accurate data converters — levels are set or readings made relative to one or more internal references, e.g., circuits based on Zener diodes in the case of dc voltage. Since the output voltage of a calibrator or the reading of a meter is proportional to the output level of the internal instrument reference

no matter what the range, any adjustment made to the reference affects all other settings or readings proportionally. Therefore, it may be possible to adjust an instrument to the new voltage scale without fully recalibrating it. Similar thinking applies to other functions such as resistance, ac voltage, and current.

A number of manufacturers intend to provide procedures to facilitate such adjustments to their products. A list of references to such procedures will be available through NCSL and GIDEP. *In any event, manufacturers' instructions should be consulted to determine if such an approach is feasible and then used to make the adjustment.*

2.2.2 Annotate control charts

Control charts are a necessity when state-of-the-art standards are being maintained at the highest accuracy levels and a good idea in any case where measurements are crucial to a company's quality-assurance efforts. These should be carefully annotated. In the case where *differences* among standards are being plotted, the change to the new representations will not appear on the control chart. Explanatory notes on such a chart will help others to reconstruct the nature of the changes and when they were made. This is especially important when there is a turnover in laboratory personnel or when problems with the quality of calibration laboratory work are perceived by others. Where actual *values* of standards are controlled and a single vertical scale used, the graphs should show a downward discontinuity on January 1, 1990. If the discontinuity is upward, a mistake has been made. See secs. 3.4, 3.5, and 4.3.2 for specific recommendations on control charting.

2.2.3 Document! Document! Document!

Failure to record changes can lead to disaster!! In keeping with normal good laboratory practice, all changes in the laboratory should be documented. An orderly sequence of adjustments should be planned, beginning with the primary standards, and changes should be recorded as they are made — not only on the calibration records of the specific equipment involved, but in a laboratory log book as well. If a mistake is made, such a record can be invaluable in determining the extent to which the population of instrumentation is affected. At the end of the sequence of adjustments to equipment within the laboratory, and before adjustments to clients' test equipment or instrumentation are made, the last item adjusted should be checked directly against the primary standards, if possible, to be sure the adjustments were made consistently, the correct sign was observed, etc.

Fig. 1. NCSL logo for indicating equipment that is calibrated or adjusted to the new unit representations (black print on a green background).

2.2.4 Use the logo

NCSL Ad Hoc Committee 91.4 has devised a logo for the purpose of marking standards, instruments, and calibration reports to indicate that the calibrations have been done in terms of V(NIST–90), Ω(NIST–90), their derivatives, or ITS–90. The logo is shown in Fig. 1.

Stickers, 1.78 cm by 1.27 cm (0.7 in. by 0.5 in.), bearing the logo will be available through the National Conference of Standards Laboratories for a nominal fee. See sec. 2.1 for the address of NCSL.

2.2.5 Annotate calibration reports

Calibration reports are a source of data or corrections for standards and many types of test equipment. Users may rely on the report information. Accordingly, it is important to annotate all calibration reports in which values are expressed in terms of the new representations, or quantities derived from them, for at least three years after the changes take effect. This should be done by means of an explicit statement such as: "The results presented in this report are expressed in terms of the NIST realization of the new 1990 representation of the volt." or by affixing the logo in a prominent place on the report.

2.3 Understanding the Role of a Unit

It is extremely important to understand the role of a unit (or a representation of a unit) in a measurement, and what effect the change of a unit has on the

measurement, as a lack of such understanding can easily lead to confusion and result in errors.[2]

Perhaps the key to understanding units is the realization that they are agreed-upon fixed reference quantities, which enable us to measure and describe quantitatively the characteristics of objects, phenomena, and their behavior. The value of a physical quantity is equal to a "label" times a unit, where the "label" is simply a number. For example, the emf of a standard cell may be written as

$$\mathrm{emf} = 1.018\,123\ \mathrm{V(NBS\text{–}72)}$$

where the number 1.018 123 is its label and V(NBS–72) its unit. The result of changing a unit, then, in the case of non-adjustable standards such as standard cells is that the label must be changed to make it consistent with the new unit. In constrast, for adjustable standards, meters, and sources, one has the option of adjusting the value of the standard, reading, or output so that the label remains the same. The lack of distinction between the units themselves and the standards used to represent them, and between the quantities being measured and the measurement results or labels, are the primary causes of error when changing units.

To illustrate the notion of labelling, consider the calibration of a nominal 100-liter vessel. One approach to calibrating the vessel would be to repeatedly pour the contents of a one-liter graduated cylinder into the vessel, counting the number of liters — including fractional pours — required to fill the vessel. Suppose the result is 100.03 liters. Now further suppose that the unit of length, the meter, is increased by 0.02% as the result of a technological breakthrough. Since volume is defined in terms of length cubed, this causes an increase in the liter of 0.06%. Consequently, the order goes out to destroy all graduated cylinders, and new cylinders, larger by 0.06%, are issued to represent the liter. Since the volume of the vessel has not changed but the volume of the cylinder used to calibrate it is larger, the number of pours will have to decrease. In fact, it decreases by 0.06% and in the new unit system the container has a capacity of 99.97 liters. Thus the unit has increased and the "label" of the fixed-size vessel has decreased — not the true volume, but what one calls the volume, or what one labels the volume to be. This is exactly the case in the forthcoming changes in the volt and ohm representations — the units will increase and the assigned values of fixed standards such as standard cells and resistors will decrease.

Note that in the discussion above, all the changes mentioned are proportional, that is, expressed as a percentage of the magnitude of the quantity discussed. The ratio of the "new" volume of any fixed-capacity container to the old volume is 0.9994. Also note that actual recalibration of a container is not necessary; one can simply multiply its label under the old unit system by 0.9994 to obtain the new label. Nowhere does one actually have to use the new graduated cylinders to measure the volume of any previously measured container.

The following two sections discuss in detail how to adjust or restandardize voltage and resistance standards to be consistent with V(NIST–90) and Ω(NIST–90).

3. Change in the U.S. Volt Representation

From July 1, 1972, through December 31, 1989, the U.S. volt representation, V(NBS–72), as maintained by NBS (now NIST) has been based on the Josephson effect using a value of the Josephson constant, K_J, of 483 593.420 GHz/V(NBS–72). As a consequence there has been no perceptible drift in V(NBS–72) during that time. There did exist, however, small differences between the volt representations maintained at different national laboratories because they chose to use different values of K_J [1, 5].

As a result of the realignment of the national volt representations to be consistent with the SI volt, on January 1, 1990, NIST will adopt a new value for K_J, namely, 483 597.9 GHz/V. This will introduce a one time step increase in the NIST volt representation of 9.264 ppm and for clarity this new representation is referred to within this document as V(NIST–90). As with V(NBS–72), there will be no significant drift in V(NIST–90) after the change. Also starting on Janu-

[2] See sec. 1.2 for a discussion of the distinction between a unit and the representation of a unit. On January 1, 1990, the representations of the volt and ohm in the United States will change. However, for illustrative purposes, in this section we equate this with a change in the unit; the principle is the same for a change in the representation of a unit.

ary 1, 1990, all NIST calibration reports for voltage standards will report the values of client standards based on V(NIST–90) using the CCE recommended terminology. The terms 'U.S. legal volt', 'NIST volt', or 'V(NIST–90)' will not be used; all values will be reported in terms of the SI volt. However, all uncertainties will be reported as if the calibration results were expressed in terms of V(NIST–90), i.e., the uncertainty of V(NIST–90) with respect to the SI volt will not be included. Thus, all uncertainties will be essentially identical to the uncertainties for calibrations previously reported in terms of V(NBS–72). (For more detail see sec. 5 regarding NIST reporting of uncertainties.)

Standards laboratories that maintain a local volt representation must "adjust" the value of their representation on January 1, 1990, to remain consistent with the NIST representation. Since most high accuracy volt representations are maintained using the Josephson effect, saturated standard cells, or solid-state voltage references, examples are given below for the "adjustment" of these standards.

3.1 Changing a Local Representation Based on the Josephson Effect

This is the easiest change to make; on January 1, 1990, start using the new value for K_J, namely, 483 597.9 GHz/V. This will produce a *decrease* in the calibrated values of your voltage standards.

3.2 Changing a Local Representation Based on Standard Cells

The emf of a standard cell is not physically adjustable and thus one must correct the assigned value of the emf to be consistent with the new value of K_J. This correction is computed as follows:

The change in the volt representation may be expressed in equation form as

$$1 \text{ V(NBS–72)} = 0.999\,990\,736 \text{ V(NIST–90)}. \qquad (3.1)$$

If e is the numerical value (i.e., label) of a standard cell based on V(NBS–72), the cell emf E is

$$E = e \text{ V(NBS–72)}, \qquad (3.2)$$

the numerical value times the unit. To express the emf in terms of V(NIST–90), we replace V(NBS–72) in eq. (3.2) with eq. (3.1), to obtain a corrected emf of

$$E = e\,[0.999\,990\,736 \text{ V(NIST–90)}]$$

or,

$$E = 0.999\,990\,736e \text{ V(NIST–90)}.$$

The correction for the new representation is thus accomplished by multiplying the previous numerical value of the cell emf by the factor 0.999 990 736 to obtain the new corrected value. This is also equivalent to subtracting 9.264 ppm of 1.0181 V, or ap-

IMPORTANT: Determining the January 1, 1990 value of a reference standard

Because V(NIST–90) becomes effective on January 1, 1990, the volt correction must be applied to the January 1, 1990, value of your reference standard. The number you use for this value depends on your current procedures. (The example below is for standard cells; the situation for solid-state references is exactly analogous.)

CASE 1. If you assume the drift rate of your cells is negligible and/or you always use the last value of a cell emf from a calibration report until the cell is recalibrated, the volt correction should be applied to the value on the last calibration report.

CASE 2. If you know the drift rate of your cells (or the drift rate of the mean of your group of cells) *and your current practice is to reassign the values to the cells to correct for the drift rate,* you must adjust the drift-corrected values, NOT the emf values from the last calibration report. For example, suppose you have a standard cell that was calibrated at NIST on April 1, 1989, with the calibrated value given as 1.018 121 66 V(NBS–72). Further, suppose that from past history you know that the cell emf is decreasing at 1 μV per year and you periodically assign new values to the cell to account for this drift. Based on V(NBS–72) the value of the cell on January 1, 1990, would be:

$$\begin{aligned} &1.018\,121\,66 \text{ V(NBS–72)} \\ &\quad - (1\ \mu\text{V/year}) \times 0.75 \text{ years} \\ &\quad = 1.018\,120\,91 \text{ V(NBS–72)}. \end{aligned}$$

The volt correction should then be applied to this calculated value.

proximately 9.43 μV, from the previously assigned cell emf.

In summary, to "correct" the value of a standard cell, given its January 1, 1990, numerical value based on V(NBS–72) [see *IMPORTANT* on page 8] multiply it by 0.999 990 736 to obtain the value for January 1, 1990, based on V(NIST–90), e.g.,

1.018 120 91 V(NBS–72)
x 0.999 990 736 V(NIST-90)/V(NBS–72)
= 1.018 111 48 V(NIST–90).

After the correction is made, the assigned value of the standard cell emf should be about 9.43 μV smaller. The change applies, of course, to all of the standard cells in the laboratory, including those used as check standards or working cells, as well as those considered to be the primary cells. The uncertainty of the value remains the same.

3.3 Changing a Local Representation Based on Solid-State References

Unlike the emf of a standard cell, the voltage of a solid-state reference can usually be adjusted. It is thus tempting to *increase* the output voltage physically by 9.264 ppm to maintain the same numerical value after the change in the volt representation.[3] We generally recommend that this procedure *not* be used with presently available solid-state references for two reasons. First, physical adjustment of the output of solid-state standards usually causes the voltage to continue to change slightly after any adjustment has been made because of settling of the adjustment potentiometer. It is therefore difficult to adjust the voltage to the exact desired value, and the value must be monitored for unusual drift after the adjustment has been made. Second, not all solid-state references have sufficient adjustment range to accommodate the change. For example, one model of a solid-state reference has an adjustment range of only 5 ppm. Even if the specified adjustment range is sufficient to accommodate the change, the adjustment potentiometer on a particular reference may unfortunately be at the top of its range and not provide sufficient adjustment. Therefore, we recommend that the procedure used for standard cells be followed for solid-state references. Change only the assigned value of the reference and do not physically adjust the actual voltage. As in sec. 3.2, the change in value is accomplished by multiplying the January 1, 1990, numerical value of the reference voltage by the factor 0.999 990 736 to obtain the new corrected value. After the correction is made the value of the reference voltage will be smaller. (See *IMPORTANT* on page 8

[3] Note the example in sec. 2.3. The liter increased in size and it now requires more liquid to fill the new 1–liter graduated cylinders.

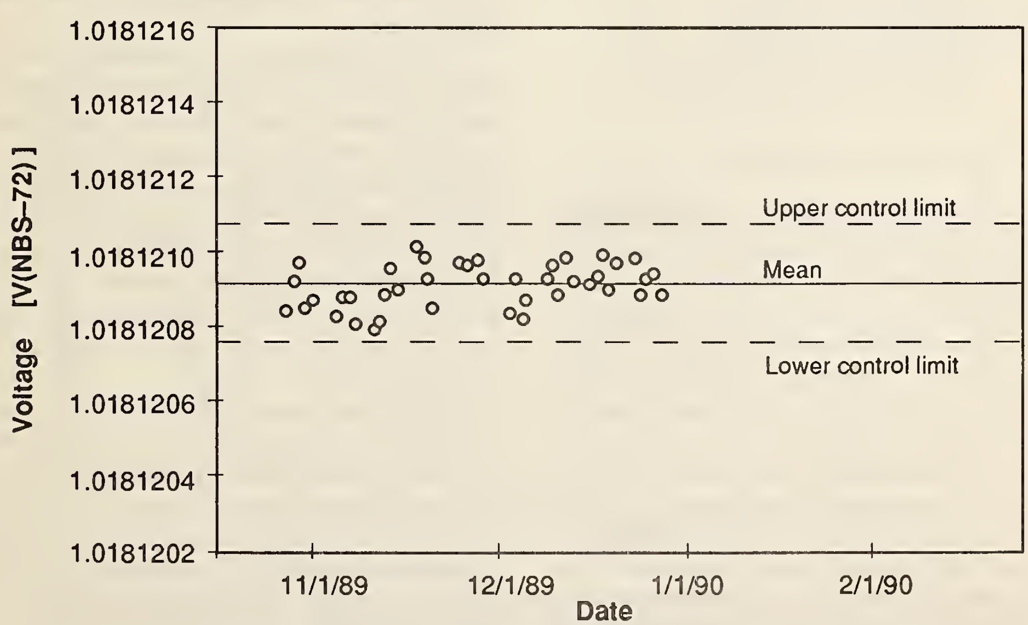

Fig. 2. Hypothetical control chart for a voltage reference prior to January 1, 1990.

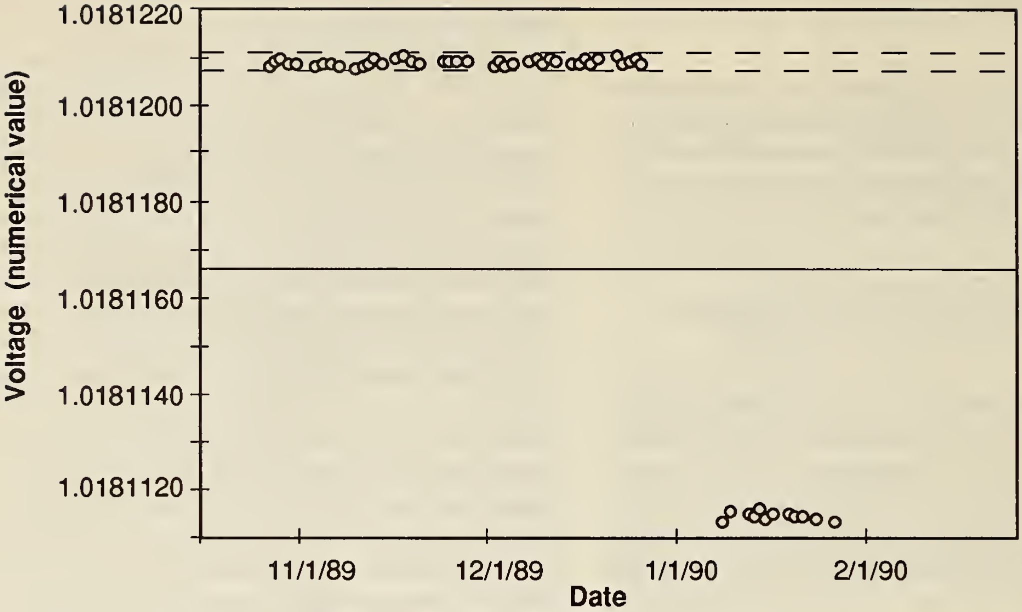

Fig. 3. Hypothetical control chart for a voltage reference with the scale adjusted to accomodate the entire change in the volt representation.

for a discussion on determining the January 1, 1990, value of a reference standard.)

For example, given the January 1, 1990, numerical value of a solid-state reference based on V(NBS–72), multiply it by 0.999 990 736 to obtain the value for January 1, 1990, based on V(NIST–90). Thus,

$$\begin{aligned}&10.000\,054\,3 \text{ V(NBS–72)}\\ &\quad \times 0.999\,990\,736 \text{ V(NIST–90)/V(NBS–72)}\\ &\quad\quad = 9.999\,961\,7 \text{ V(NIST–90)}\,.\end{aligned}$$

3.4 Updating Control Charts

Control charts of reference voltages (plots of reference voltages vs time), should be used in every standards laboratory as a means of determining whether or not the reference voltages (and other process parameters) are in a state of statistical control [15]. Figure 2 (on page 9) shows a hypothical reference voltage control chart with upper and lower control limits that one might have generated up to the end of 1989. The change in the volt representation on January 1, 1990, will introduce an unacceptably large step change in later data plotted on the chart. In this example, the mean value of the plotted points is 1.018 120 91 V(NBS–72). Applying the correction for V(NIST–90) will change the mean value to 1.018 111 48 V(NIST–90) which will obviously cause newly plotted points to be off the graph. If the range of the graph is increased to encompass both the old and new points, the distance between the upper and lower control limits will be so small as to be indistinguishable from the points as shown in Fig. 3. Therefore, in order to continue to be useful, the control chart will need to be modified. Two alternative solutions to this problem are suggested below.

(1) To avoid the time consuming job of manually replotting all of the data on control charts, one may simply provide a second y–axis to be used for plotting data obtained after January 1, 1990. Figure 4 shows how this might be done. The additional y–axis scale on the right is shifted by –9.264 ppm of the mean value, or –9.43 μV for this example. Thus the lines drawn to represent the mean value and upper and lower control limits continue uninterrupted. *Do not fail to note on the chart that the change is effective on January 1, 1990.*

(2) In many cases control charts are generated automatically by a computer. If the computer charting program provides the capability of having a second y–axis scale, the approach suggested in (1) above may be used. However, with computer charting programs it is often necessary to generate a completely new control chart with the data taken before January 1, 1990, "corrected" to V(NIST–90). *(Note: Do not alter permanant data records, see sec. 3.5.)* The mean and

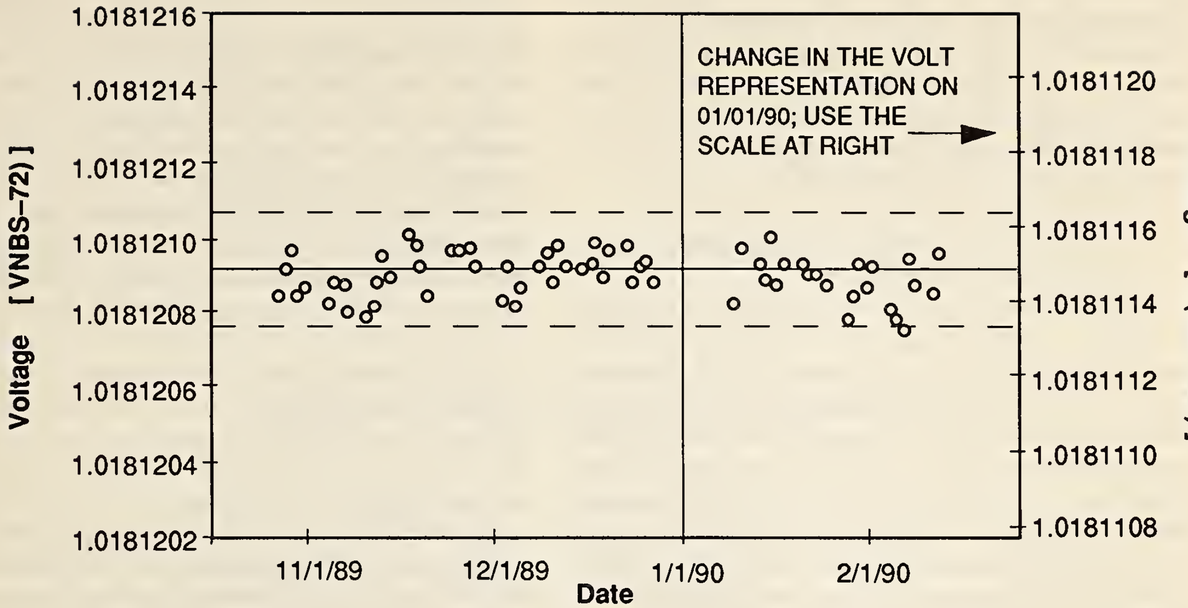

Fig. 4. Hypothetical control chart for a voltage reference with an added scale on the right to be used for all data after January 1, 1990.

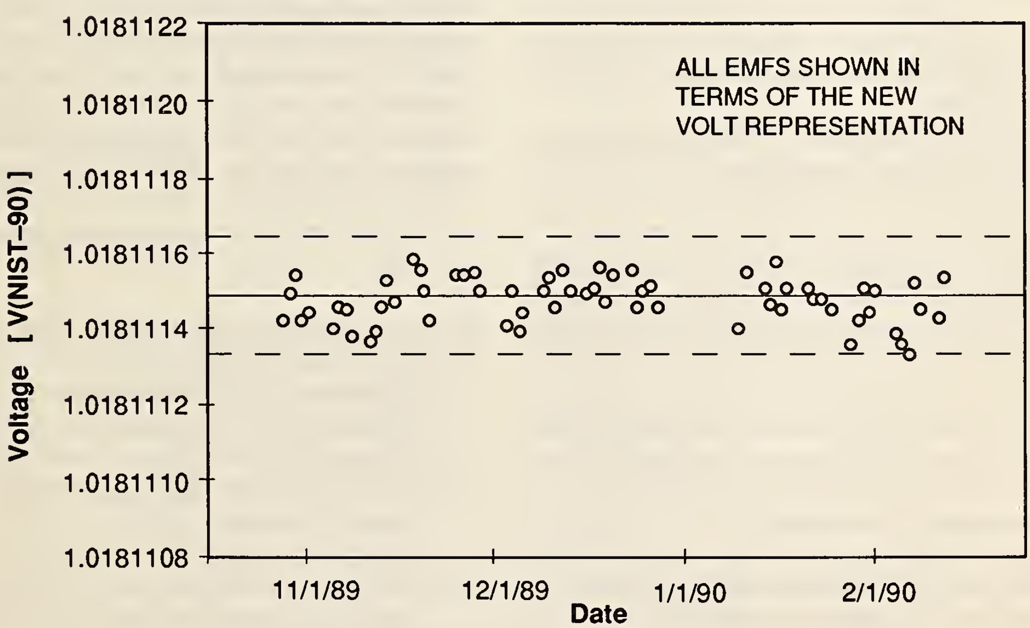

Fig. 5. Hypothetical control chart for a voltage reference with the original scale modified to the new volt representation and the data before January 1, 1990, "corrected" to the new representation.

upper and lower control limits are also shifted by the same correction to provide a continuous record as shown in Fig. 5. Note that the plotted values before January 1, 1990, are a construct; they are shifted only for the purpose of examining the performance of a particular voltage reference using the control chart. *Do not use them as the calibrated values.*

3.5 Do Not Correct Pre-1990 Data

Most standards laboratories maintain, or should maintain, a historical record of the calibrations of their standards and the intercomparison measurements made among their standards. On January 1, 1990, there will be a step change in the values of the voltage references if the laboratory has properly adjusted their local volt representation to be consistent with that of NIST. There may be a temptation to go back and apply the change to all data prior to January 1, 1990, to make them consistent with later data. *This is incorrect; data taken prior to January 1, 1990, should NOT be corrected to V(NIST–90) because V(NBS–72) was in fact the legal unit at the time.*

It may be the case that these historical records are maintained in a computerized data base. *There are so many dangers associated with correcting the data in a computerized data base that we DO NOT recommend changing the original data.* Some of the reasons follow:

- It is possible that some data files may be overlooked during the "correction" process and will thus be incorrect.
- The "correction" process may be inadvertently applied twice to a particular data file.
- The correction may be applied with the wrong sign.
- The user or another user may forget that the data is to be used only for control charts, and attempt to use the numbers as the calibrated reference values.

In all these cases it is possible that, even if the changes are carefully documented, an error in the correction process may result in erroneous data that can never be properly corrected.

3.6 Effect of the International Temperature Scale of 1990 on Standard Cells

On January 1, 1990, the International Practical Temperature Scale of 1968 (IPTS–68) will be superseded by the International Temperature Scale of 1990 (ITS–90) [3, 16]. As a result of this change in scale, temperatures will change about 0.006 to 0.008°C in the range relevant to voltage standards (28°C to 37°C); see ref. 3 reprinted in Appendix 3. The change is analogous to the change in the volt and ohm representations, i.e., the temperature scale is shifting and the "labels" will change but not the actual temperatures. *This change may affect laboratories using standard cells in an oil bath or in an air bath where the temperature is measured using a calibrated platinum resistance thermometer or other temperature measuring device calibrated in terms of IPTS–68.* Not affected are laboratories with only solid-state references, or standard cell air baths containing their own imbedded temperature monitor such as a thermistor or a mercury-in-glass thermometer that is not removed and calibrated. Standards in the latter category define their own local temperature scale and there is no need, or reason, to make any adjustment to bring them into conformance with ITS–90. Also not affected are those laboratories that do not "temperature correct" the values of their standard cells (presumably only because of relatively low accuracy requirements or excellent temperature bath stability).

The introduction of ITS–90 will result in temperature values being shifted downward by about 7 mK at 30°C. Thus if one were to maintain a constant-temperature oil bath at 30.000°C that does not physically change temperature, after January 1, 1990, the "new" temperature would be 29.993°C. If one follows traditional procedures after the change and applies a temperature correction to the standard cells because the cells were not at their expected or "nominal" temperature of 30°C, the application would cause the emf's to be decreased by 0.4 μV when in fact they did not change. There are two possible ways of avoiding this error.

(1) One may physically adjust the temperature of the oil bath upward by 7 mK to bring it into agreement with the new temperature scale. This would produce a real decrease in the cell emf's of about 0.4 μV. Control charts are handled in exactly the same manner as for the volt representation change. It is also advisable to measure the emf change of the cells in the bath (referenced to another group of cells whose temperature is not physically changed) to determine the exact change in emf, rather than relying on the Wolff or International Temperature Formula.

(2) If the cells are always kept in the bath and are

not removed and sent to another laboratory for calibration, the nominal temperature of the bath may be simply adopted as 29.993°C. The nominal temperature of a bath is just a value chosen to be considered the normal operating temperature of the bath, and need not be closely related to any actual measured temperature. The nominal temperature is only a convenient numerical reference. To see how this works, a discussion of the temperature correction process follows.

When the cells are measured, their temperature is also measured and a correction is applied if their temperature is different from the nominal temperature. Later, when they are again measured, a second temperature correction is applied for the difference between the current temperature and the nominal temperature. The important parameter is the difference between the two temperature corrections; the nominal temperature drops out of the equation entirely.

4. Change in the U. S. Ohm Representation

The last change in the U. S. representation of the ohm, $\Omega(\text{NBS–48})_t$, occurred on January 1, 1948, when the system of electrical units designated as "international" was superseded by units derived from the fundamental units of length, mass, and time. These have now evolved to become the International System of Units or SI. Since that time $\Omega(\text{NBS–48})_t$ has been based on the mean resistance of reference groups of 1–Ω resistors whose mean values were thought to be constant with time. Quantized Hall resistance measurements made on a regular basis since August of 1983 at NIST indicate that $\Omega(\text{NBS–48})_t$, based on the same particular reference group of five 1-Ω resistors in use since 1972, has a drift rate of (-0.0529 ± 0.0040) ppm/year [14]. In calibration reports for resistance standards issued by NIST prior to January 1, 1990, the reported resistance values have *not* been adjusted to eliminate the drift of $\Omega(\text{NBS-48})_t$.

4.1 Conversion Factor

As discussed earlier, on January 1, 1990, Ω(NIST–90) will be based on the quantum Hall effect in which a resistance is related to the fundamental constants h/e^2. The quantized Hall resistance, R_H, is defined as the quotient of the Hall voltage U_H of the ith plateau to the current I in the Hall device and is given by

$$R_H(i) = U_H(i)/I = R_K/i, \qquad (4.1)$$

where R_K, the von Klitzing constant, is equal to h/e^2 and i is an integer. The value of Ω(NIST–90) will be consistent with the internationally accepted conventional value of the von Klitzing constant, i.e.,

$$R_{K\text{-}90} = 25\,812.807\ \Omega, \qquad (4.2)$$

exactly. This conventional value is believed to be consistent with the true SI value to within a 0.005 Ω assigned one-standard-deviation uncertainty, corresponding to a relative uncertainty of 0.2 ppm [1]. This change will *decrease* the numerical value of the mean resistance of the NIST reference group by 1.69 ppm and eliminate the drift of the U. S. representation of the ohm, as shown in Fig. 6. The conversion factor for adjusting values of resistance standards in the U.S. on January 1, 1990, is as follows:

$$1\ \Omega(\text{NBS–48})_{01/01/90} = 0.999\,998\,31\ \Omega(\text{NIST–90}). \qquad (4.3)$$

(Recall that $\Omega(\text{NBS–48})_t$ has a date subscript to indicate the time dependency of the U. S. representation of the ohm before January 1, 1990.)

In theory, the *assigned values* of all standard resistors based on NIST calibrations should be *decreased* by 1.69 ppm on January 1, 1990. The change in resistance of a standard from its last NIST calibration up to January 1, 1990, should be included if its drift rate is known. Also, the *drift rates* of standard resistors that are based on NIST calibrations should be *decreased* by 0.0529 ppm/year.

In practice, it is recommended that adjustments only be made to the values of standard resistors whose calibration uncertainties are roughly within ten times the January 1, 1990, change in the U. S. representation of the ohm. This means that only the values of standard resistors based on Ω(NIST–90) with reported uncertainties of 20 ppm or less need to be adjusted. These include standard resistors calibrated by NIST in the decade resistance levels from 0.001 Ω to 1 MΩ.

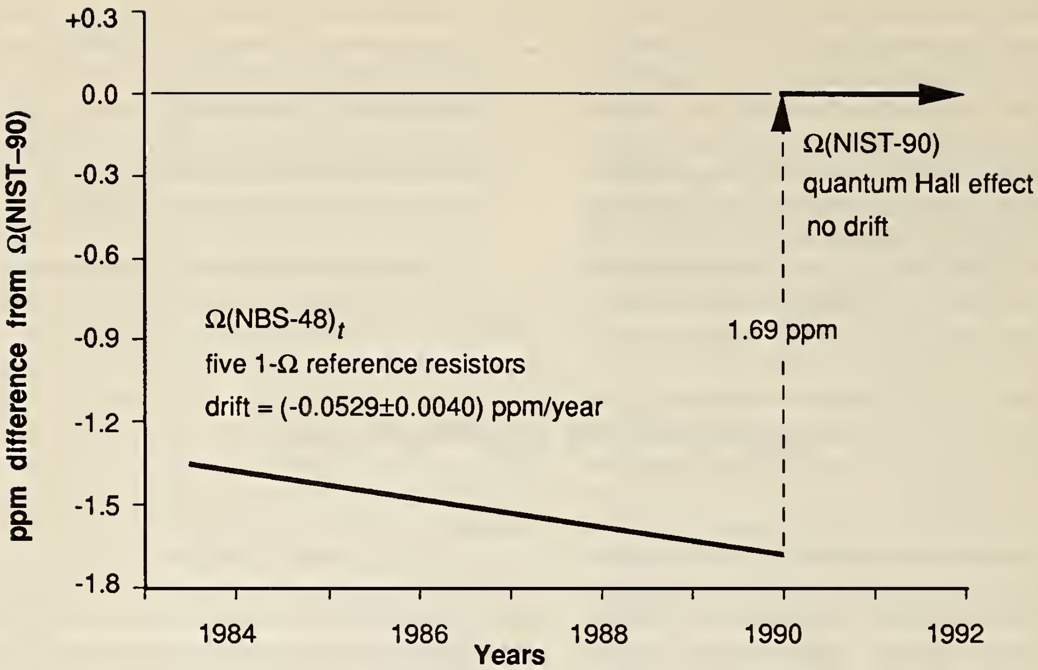

Fig. 6. Time dependence of the U.S. ohm representation.

Also, for standards in this resistance range, it is recommended that adjustments only be made to their drift rates if these are 1 ppm/year or smaller in absolute magnitude. It is difficult to determine drift rates of resistors to better than 10%, and neglecting the -0.0529 ppm/year drift of Ω(NBS–48)$_t$ prior to January 1, 1990, would result in errors of 5% or less for standard resistor drift rates with absolute magnitudes of 1ppm/year or larger.

4.2 Examples

The following examples are given to illustrate the method of calculating and applying these changes. (Note that the drift rate of Ω(NBS–48)$_t$ may be rounded to 0.05 ppm/year for these examples with negligible effect.)

Example 1: A 1-Ω standard resistor was calibrated at NIST on 09/15/88 and reported to have a value of 0.999 998 91 Ω(NBS–48)$_{09/15/88}$. From previous NIST calibrations, its drift rate was calculated to be -0.10 ppm/year. Note that this drift rate includes the drift of Ω(NBS–48)$_t$. What are its new value and drift rate on 01/01/90?

Solution: Calculate the change in resistance ΔR due to drift from 09/15/88 to 01/01/90:

$$\begin{aligned}\Delta R &= \text{drift rate x time interval}\\ &= (-0.10\ \text{ppm/year}) \times (01/01/90 - 09/15/88)\\ &= (-0.10\ \text{ppm/year}) \times 1.29\ \text{years}\\ &= -0.13\ \text{ppm}\\ &= -0.000\,000\,13\ \Omega(\text{NBS–48})_{01/01/90-09/15/88}.\end{aligned}$$

Add ΔR to the value for 09/15/88 to obtain the resistance R for 01/01/90 based on Ω(NBS–48)$_t$:

$$\begin{aligned}R(01/01/90) &= 0.999\,998\,91\ \Omega(\text{NBS-48})_{09/15/88} + \Delta R\\ &= 0.999\,998\,91\ \Omega(\text{NBS–48})_{09/15/88}\\ &\quad - 0.000\,000\,13\ \Omega(\text{NBS–48})_{01/01/90-09/15/88}\\ &= 0.999\,998\,78\ \Omega(\text{NBS–48})_{01/01/90}.\end{aligned}$$

Multiply by the conversion factor [eq.(4.3)] to obtain the resistance R for 01/01/90 based on Ω(NIST–90); for convenience in these *Guidelines*, this resistance will be denoted as R_0:

$$\begin{aligned}R_0 &= 0.999\,998\,78\ \Omega(\text{NBS–48})_{01/01/90}\\ &\quad \times 0.999\,998\,31\ \Omega(\text{NIST–90})/\Omega(\text{NBS–48})_{01/01/90}\\ &= 0.999\,997\,09\ \Omega(\text{NIST–90}).\end{aligned}$$

Calculate the new drift rate D:

$$
\begin{aligned}
D &= \text{old drift rate} + \text{drift of } \Omega(\text{NBS–48})_t \\
&= -0.10 \text{ ppm/year} - 0.05 \text{ ppm/year} \\
&= -0.15 \text{ ppm/year.}
\end{aligned}
$$

Therefore, on 01/01/90 the new value for this 1–Ω standard resistor is 0.999 997 09 Ω(NIST–90) and its new drift rate is -0.15 ppm/year.

Example 2: A 10–kΩ standard resistor was calibrated at NIST on 03/15/89 and reported to have a value of 10 000.065 $\Omega(\text{NBS–48})_{03/15/89}$. From previous NIST calibrations, its drift rate was calculated to be +0.20 ppm/year. What are its new value and drift rate on 01/01/90?

Solution:

$$
\begin{aligned}
\Delta R &= (+0.20 \text{ ppm/year}) \times 0.80 \text{ year} \\
&= +0.16 \text{ ppm} \\
&= +0.0016\ \Omega(\text{NBS–48})_{01/01/90\text{-}03/15/89}
\end{aligned}
$$

$$
\begin{aligned}
R(01/01/90) &= 10\,000.065\ \Omega(\text{NBS–48})_{03/15/89} \\
&\quad + 0.0016\ \Omega(\text{NBS–48})_{01/01/90\text{-}03/15/89} \\
&= 10\,000.067\ \Omega(\text{NBS–48})_{01/01/90}
\end{aligned}
$$

$$
\begin{aligned}
R_0 &= 10\,000.067\ \Omega(\text{NBS–48})_{01/01/90} \\
&\quad \times 0.999\,998\,31\ \Omega(\text{NIST–90})/\Omega(\text{NBS–48})_{01/01/90} \\
&= 10\,000.050\ \Omega(\text{NIST–90})
\end{aligned}
$$

$$
\begin{aligned}
D &= +0.20 \text{ ppm/year} - 0.05 \text{ ppm/year} \\
&= +0.15 \text{ ppm/year.}
\end{aligned}
$$

Therefore, on 01/01/90 the new value for this 10–kΩ standard resistor is 10 000.050 Ω(NIST–90) and its new drift rate is +0.15 ppm/year.

Example 3: A 1–MΩ standard resistor was calibrated at NIST on 06/15/87 and reported to have a value of 1 000 067 $\Omega(\text{NBS–48})_{06/15/87}$. Previous data indicate it has a drift rate of +2.0 ppm/year. What are its new value and drift rate on 01/01/90?

Solution:

$$
\begin{aligned}
\Delta R &= (+2.0 \text{ ppm/year}) \times 2.54 \text{ years} \\
&= 5 \text{ ppm} \\
&= 5\ \Omega(\text{NBS–48})_{01/01/90\text{-}06/15/87}
\end{aligned}
$$

$$
\begin{aligned}
R(01/01/90) &= 1\,000\,067\ \Omega(\text{NBS–48})_{06/15/87} \\
&\quad + 5\ \Omega(\text{NBS–48})_{01/01/90\text{-}06/15/87} \\
&= 1\,000\,072\ \Omega(\text{NBS–48})_{01/01/90}
\end{aligned}
$$

$$
\begin{aligned}
R_0 &= 1000\,072\ \Omega(\text{NBS–48})_{01/01/90} \\
&\quad \times 0.999\,998\,31\ \Omega(\text{NIST–90})/\Omega(\text{NBS–48})_{01/01/90} \\
&= 1\,000\,070\ \Omega(\text{NIST–90})
\end{aligned}
$$

$$D = +2.0 \text{ ppm/year.}$$

Therefore, on 01/01/90 the new value for this 1 MΩ standard resistor is 1 000 070 Ω(NIST–90). Its drift rate remains at +2.0 ppm/year because the drift rate of $\Omega(\text{NBS–48})_t$ is negligible compared to the drift rate of this standard resistor.

4.3 Updating Predicted Values and Control Charts

The usual method of determining whether resistance measurements are in a state of statistical control is to examine the behavior of check standards. Check standards are resistors, of quality equal to that of reference resistors, which are treated as unknowns to monitor the operation of a resistance measurement system. The measured value of a check standard, or any other standard, can be (1) compared to its predicted value, or (2) plotted on a control chart with upper and lower control limits to give evidence of the quality of the measurements. The system is in statistical control when the measured values lie within a reasonable confidence interval. It is important when updating predicted values or control charts of standards to keep intact the original pre-1990 data (see sec. 3.5 on correcting historical data).

4.3.1 Predicted values

The resistances of well-aged standard resistors exhibit a linear functional relationship with time if the resistors are not subjected to extreme temperature changes or mechanical disturbances. The linear equation for this model to predict the value of a standard at some future time can be written as:

$$R'(t) = R_0 + (t - t_0)D, \tag{4.4}$$

where $R'(t)$ is the predicted value of the standard at time t, R_0 is the value for t_0 = 1990.00 years, and D is the new drift rate. Examples of calculations of R_0 and D are given in sec. 4.2. The difference between the measured and predicted values of the standard can be used to determine if the measurement system is in statistical control, i.e.,

TABLE II

Correction Values in ppm to Convert to Ω(NIST–90)

	1985	1986	1987	1988	1989
1 Jan	-1.426	-1.478	-1.531	-1.584	-1.637
1 Feb	-1.430	-1.483	-1.536	-1.589	-1.642
1 Mar	-1.434	-1.487	-1.540	-1.593	-1.646
1 Apr	-1.439	-1.491	-1.544	-1.597	-1.650
1 May	-1.443	-1.496	-1.549	-1.602	-1.654
1 Jun	-1.447	-1.500	-1.553	-1.606	-1.659
1 Jul	-1.452	-1.505	-1.558	-1.610	-1.663
1 Aug	-1.456	-1.509	-1.562	-1.615	-1.668
1 Sep	-1.461	-1.514	-1.567	-1.619	-1.672
1 Oct	-1.465	-1.518	-1.571	-1.624	-1.677
1 Nov	-1.470	-1.522	-1.575	-1.628	-1.681
1 Dec	-1.474	-1.527	-1.580	-1.633	-1.686

$$-\mathrm{CL} < R(t) - R'(t) < +\mathrm{CL}, \tag{4.5}$$

where $R(t)$ is the measured value of the standard and CL is the confidence level limit.

This is probably the easiest method to determine the control state of the measurement process, especially if the data analysis is being done by a computer. These equations can be incorporated into a computer program that indicates an error condition or flag whenever the difference between the measured and predicted values of the standard exceed the confidence level limits.

4.3.2 Control charts

As a result of implementing the new representation of the ohm, Ω(NIST–90), the control charts of standards after January 1, 1990, will display significant changes both in the measured values and subsequent drift rates. After January 1, 1990, it will be difficult to determine graphically if the measurements are in a state of statistical control until a sufficient data base is collected for the standard. Therefore, it will be necessary to correct the pre-1990 data on the standard for the change and drift of $\Omega(\text{NBS–48})_t$ prior to January 1, 1990. The correction c to the pre-1990 data will be a linear function with time and can be expressed in ppm as:

$$c = -1.69 \text{ ppm} - (0.0529 \text{ ppm/year})(t - t_0), \tag{4.6}$$

where t_0 = 1990.00 years, and t is the measurement date expressed in years and is ≤ 1990.00. For the convenience of the reader, Table II gives the correction c for monthly intervals starting from 1985.

A model of a control chart for monitoring the value of a 1–Ω standard after January 1, 1990, is shown in Fig. 7. The filled-circle symbols represent measured values of the standard. The open-circle symbols represent the pre-1990 data that was adjusted using the corrections listed in Table II. As examples, two of these corrections are printed on the chart, namely, -1.64 ppm and -1.69 ppm for January 1, 1989, and January 1, 1990, respectively. The corrected data (open-circle symbols) are used to determine a new trend line for the continuation of the control chart after January 1, 1990. This can be done graphically, or more precisely by the method of least squares for linear regression. The upper and lower limit lines about the trend line correspond to confidence level limits of ±0.10 ppm. *Note that the drift rate of the standard has changed as a result of eliminating the drift of* $\Omega(\mathit{NBS–48})_t$. Before January 1, 1990, the drift rate of the standard was +0.067 ppm/year; after January 1, 1990, its drift rate is +0.014 ppm/year.

The range of corrections for the control chart in Fig. 7 was expanded to include the -1.69 ppm shift on

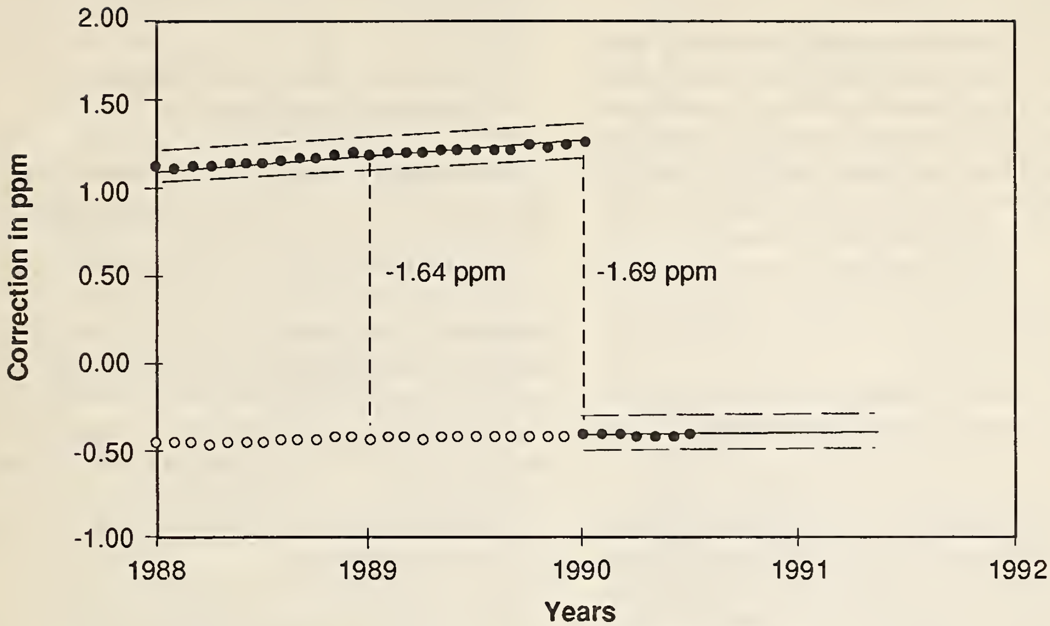

Fig. 7. Hypothetical low resolution control chart of a 1–Ω standard.

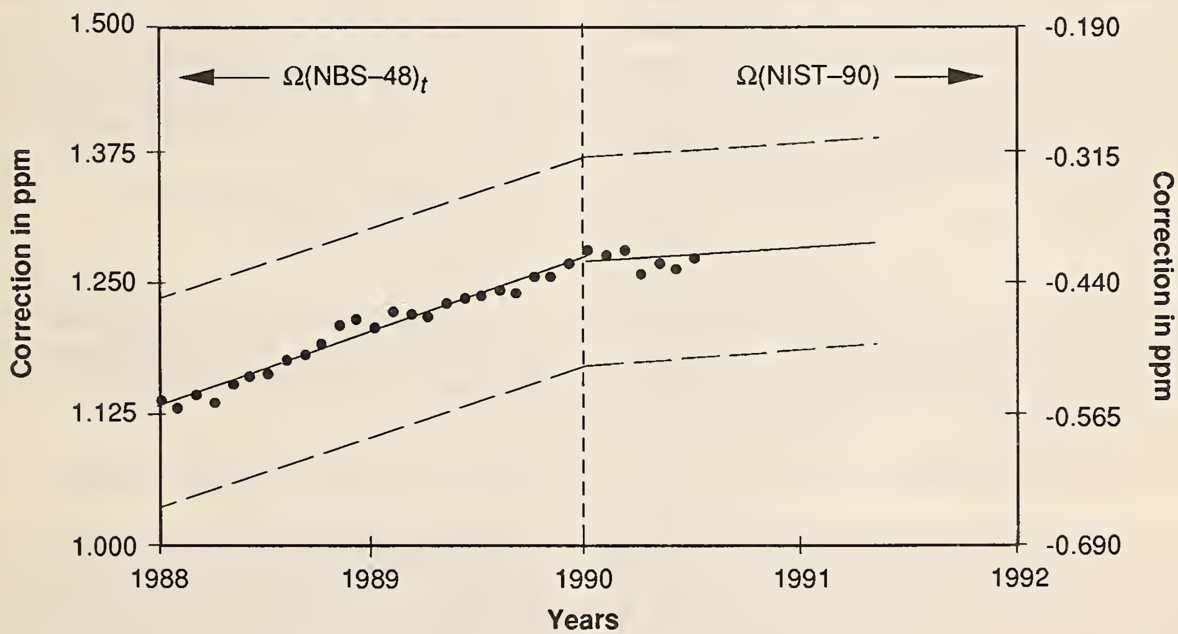

Fig. 8. Hypothetical high resolution control chart of a 1–Ω standard. The added scale on the right is used for all data after January 1, 1990.

January 1, 1990. Consequently, it is difficult to see the variability of the measurements and the apparent change in the drift of the standard. The resolution of the control chart can be increased by creating one with two scales for the y–axis. The y–axis scale on the right is offset by -1.69 ppm to force the trend line to be continuous on January 1, 1990. This is shown in Fig. 8. Note that the scale on the left refers to measurements made before January 1, 1990, while the scale on the right refers to measurements made on and after January 1, 1990. With this control chart it is easier to determine the quality of the measurement process.

4.4 Effect of the International Temperature Scale of 1990 on Standard Resistors

The region of temperature of critical importance to resistance measurements is from 20°C to 30°C. Resistors are usually maintained in a laboratory environment at 23°C or in an oil bath at 25°C, and the temperature coefficients of resistors are usually determined over the temperature range from 20°C to 30°C. On January 1, 1990, the International Temperature Scale of 1990 (ITS–90) will supersede the International Practical Temperature Scale of 1968 (IPTS–68). ITS–90 is not expected to be finalized until the latter part of 1989. However, for most applications to resistance measurements, preliminary analysis of available temperature data indicates that ITS–90 (over the temperature range from 20°C to 30°C) can be approximated as a linear shift in temperature, Δt,

$$\begin{aligned} t_{90} &\approx t_{68} + \Delta t \\ &\approx t_{68} - (6 \pm 1)\ \text{mK}, \end{aligned} \tag{4.7}$$

where t_{90} and t_{68} are the Celsius temperatures defined by ITS–90 and IPTS–68, respectively.

ITS–90 will affect resistance measurements primarily in three areas:

(1) Oil Bath Temperatures

On January 1, 1990, the NIST resistance laboratory will physically adjust the temperature of its 25.000°C oil baths as based on IPTS–68 so that they will become 25.000°C oil baths as based on ITS–90. (That is, the temperature of the baths will be physically increased by about 6 mK.) *To remain consistent with NIST, it is imperative that other laboratories also conform to ITS–90.* The following analysis assumes such conformance. Laboratories should consult *Guidelines for Realizing the International Temperature Scale of 1990 (ITS–90)* [16].

(2) Resistance Changes and Temperature Coefficients of Resistors

The resistance-temperature curve for resistors over the interval 20°C to 30°C can be represented by

$$R(t) \approx R'\,[1 + \alpha(t - t_r) + \beta(t - t_r)^2], \tag{4.8}$$

where $R(t)$ is the resistance at temperature t, R' is the resistance at a reference temperature t_r, α is the slope of the curve at t_r, and β determines the curvature at any temperature. The reference temperature t_r is usually 25°C for oil-type resistors and 23°C for air-type resistors.

To indicate which temperature scale is in use, eq. (4.8) can be written as

$$R(t_{68}) \approx R'_{68}[1 + \alpha_{68}(t_{68} - t_r) + \beta_{68}(t_{68} - t_r)^2] \tag{4.9}$$

$$R(t_{90}) \approx R'_{90}[1 + \alpha_{90}(t_{90} - t_r) + \beta_{90}(t_{90} - t_r)^2], \tag{4.10}$$

where the subscripts 68 and 90 denote that the temperature and coefficients are based on IPTS–68 and ITS–90, respectively. The value of t_r is the same for both equations. Using eq. (4.7) along with eqs. (4.9) and (4.10), one can derive expressions relating the coefficients based on the different temperature scales. Neglecting negligible terms, these equations are:

$$R'_{90} \approx R'_{68}[1 - \alpha_{68}(\Delta t) + \beta_{68}(\Delta t)^2], \tag{4.11}$$

$$\alpha_{90} \approx \alpha_{68} - 2\beta_{68}(\Delta t), \tag{4.12}$$

$$\beta_{90} \approx \beta_{68}\,. \tag{4.13}$$

The change in resistance at the reference temperature, $\Delta R(t_r)$, resulting from the implementation of ITS–90 can be calculated from eq. (4.11) and expressed as

$$\Delta R(t_r) = R'_{90} - R'_{68} \approx R'_{68}[-\alpha_{68}(\Delta t) + \beta_{68}(\Delta t)^2]. \tag{4.14}$$

Since Δt is small, the β term in this equation can be neglected. The maximum change in resistance for resistors with α's within the limits ±10 ppm/K would be ±0.06 ppm. This may be significant at the 1–Ω level; however, for most resistance measurements this change is negligible.

In theory the values of all α's of standard resistors should be adjusted on January 1, 1990, using eq. (4.12);

however, in practice the magnitude of this adjustment is negligible for most resistors. Since the values of β are approximately -0.5 ppm/K^2 for typical manganin-type resistors, α_{90} for this type of resistor differs from α_{68} by less than 0.01 ppm/K in absolute value. The effect is less for Evanohm-type resistors since their values of β are approximately -0.05 ppm/K^2. The β coefficients do not change value, as shown in eq. (4.13).

As an example to illustrate the changes resulting from implementing ITS–90, consider example 1 from sec. 4.2 and assume that the 1–Ω resistor has an α_{68} of +1.67 ppm/K and a β_{68} of -0.50 ppm/K^2. What are its change in resistance and its new temperature coefficients of resistance on January 1, 1990?

<u>Solution:</u> Calculate the change in resistance $\Delta R(t_r)$. From eq. (4.14), neglecting β_{68},

$$\begin{aligned}\Delta R(t_r) &\approx R'_{68}[-\alpha_{68}(\Delta t)]\\ &\approx 0.999\,997\,09\ \Omega(\text{NIST–90}) \times (-0.000\,001\,67/\text{K})\\ &\qquad \times (-0.006\ \text{K})\\ &\approx 0.000\,000\,01\ \Omega(\text{NIST–90}).\end{aligned}$$

Its new value R which includes the change resulting from the effect of ITS–90 is:

$$\begin{aligned}R &\approx R_0 + \Delta R(t_r)\\ &\approx 0.999\,997\,09\ \Omega(\text{NIST–90})\\ &\qquad + 0.000\,000\,01\ \Omega(\text{NIST–90})\\ &\approx 0.999\,997\,10\ \Omega(\text{NIST–90}).\end{aligned}$$

Calculate the new temperature coefficients of resistance:

$$\begin{aligned}\alpha_{90} &\approx \alpha_{68} - 2\beta_{68}(\Delta t)\\ &\approx (0.000\,001\,67/\text{K}) - [2 \times (-0.000\,000\,50/\text{K}^2)]\\ &\qquad \times (-0.006\ \text{K})\\ &\approx 0.000\,001\,66/\text{K}\\ &\approx +1.66\ \text{ppm/K}\end{aligned}$$

$$\beta_{90} \approx \beta_{68} \approx -0.50\ \text{ppm/K}^2.$$

Therefore on 01/01/90 the new value for this 1–Ω standard resistor is 0.999 997 10 Ω(NIST–90) and its α_{90} is +1.66 ppm/K, and its β_{90} is -0.50 ppm/K^2. Note that the changes that result from implementing ITS–90 are small and are only significant for resistance measurements at the 0.01 ppm level of accuracy.

(3) Control Charts

The implementation of ITS–90 will affect the trend lines of control charts in addition to the alterations discussed in sec. 4.3.2. The effect is only a shift of the trend line and for most resistance measurements is negligible. However, this shift, $\Delta R(t_r)$ may be significant at the 1–Ω level and may be calculated from eq. (4.14). It is +0.01 ppm in the previous example.

4.5 Summary

To conform to the new representation of the ohm, Ω(NIST–90), and ITS–90 (as it affects resistance measurements), it is recommended that on January 1, 1990, the following steps be taken:

1. Calculate R_0, the resistance for 01/01/90 based on Ω(NIST–90) (see examples in sec. 4.2) for resistors with uncertainties of 20 ppm or less.
2. Calculate D, the new drift rate after 01/01/90 (see examples in sec. 4.2) for resistors with drift rates with absolute magnitudes of < 1 ppm/year.
3. The temperatures of oil baths operating at 25.000°C defined by IPTS–68 must be increased by 6 mK to convert to ITS–90.
4. In general, there is no need to calculate new α coefficients for resistors. The change in the absolute magnitude of α for most resistors would be < 0.01 ppm/K. Also, the β coefficients do not change.
5. Calculate $\Delta R(t_r)$ (defined in eq. 4.14), the change in resistance resulting from the implementation of ITS–90, for Thomas-type (or equivalent) 1–Ω resistors with α's having absolute magnitudes > 1.7 ppm/K. This change is negligible for most other resistance measurements.
6. The new value of resistance, R, for Thomas-type (or equivalent) 1–Ω resistors is the algebraic sum of items 1 and 5. That is, $R \approx R_0 + \Delta R(t_r)$.
7. Update procedure for calculating predicted values of check standards as outlined in sec. 4.3.1.
8. Update procedure for monitoring resistance measurements using control charts as outlined in sec. 4.3.2.

Most laboratories will be consistent with Ω(NIST–90) if the above recommended procedural steps are followed. However, there may be some critical resistance measurements where the effect of ITS–90 is significant and steps 4, 5, and 6 would have to be investigated in greater detail.

5. The Reporting of Calibration Results by NIST

The CCE believes that (i) the appearance of creating a new unit system outside of the SI must be avoided; (ii) the new volt and ohm representations based on the Josephson and quantum Hall effects will be completely satisfactory for the great majority of applications (i.e., it will rarely be necessary to distinguish between the new representations and the SI units); and (iii) any differences among the volt and ohm representations of different laboratories will be negligible from the point of view of the great majority of users (i.e., it will rarely be necessary to distinguish between the representations of different laboratories). Therefore, the CCE and CIPM have recommended that national standards laboratories avoid the use of subscripts or other distinguishing symbols of any sort on either unit symbols (i.e., V, Ω) or quantity symbols (i.e., E, R), when reporting the results of calibrations carried out in terms of the new volt and ohm representations. Examples of such subscripts are those denoting particular laboratories or dates such as V_{NIST}, V_{90}, E_{NIST}, or E_{90}.

The CCE's solution to the reporting problem, which was affirmed by the CIPM and which all national standards laboratories are requested to use, is indicated in the following variation of the example given by the CCE (the treatment of resistance measurements is strictly analogous) [1, 3, 6]:

The emf E of an unknown standard cell calibrated in terms of a representation of the volt based on the Josephson effect and the conventional value of the Josephson constant K_{J-90}, may be rigorously expressed in terms of the SI volt V as (to be specific):

$$E = (1.018\ 123\ 45)\ \mathrm{V} \pm \varepsilon, \tag{5.1}$$

where ε represents the total uncertainty (in volts) and is composed of the following two components: ΔE, the combined uncertainty associated with the calibration itself and with the realization of the Josephson effect volt representation at the particular standards laboratory performing the calibration; and ΔA, the uncertainty with which the ratio K_{J-90}/K_J is known (i.e., it is assumed that $K_{J-90}/K_J = 1 \pm \Delta A$). According to the CIPM, ΔA may be taken as 0.4 ppm (1σ).

Since, by international agreement, ΔA is common to all laboratories and is not relevant for traceability to national standards, the two uncertainties ΔE and ΔA need not be formally combined to obtain the total uncertainty but may be separately indicated. Hence, the measured emf E may be expressed as

$$E = (1.018\ 123\ 45)\ \mathrm{V} \pm \Delta E \tag{5.2}$$

for all practical purposes of precision electrical metrology and trade, with ΔA appearing separately on the calibration certificate when the precision of the calibration warrants it. If, for example, $\Delta E/E$ is significantly greater than 0.4 ppm, ΔA may be omitted with negligible effect.

In fact, the CCE approach is not too dissimilar to NIST practice prior to January 1, 1990, when calibration results were reported in terms of the 'U.S. legal volt' as derived from the Josephson effect, but with the uncertainty corresponding to ΔA always omitted. In response to the CCE recomendation, starting January 1, 1990, NIST will include with all calibration reports an information sheet discussing the existence of the additional uncertainty component ΔA and giving its value. An example of the wording that will be used on a NIST Report of Calibration for a standard cell enclosure, and which in part is a variation of the wording used in an example developed by the CCE, is given in Fig. 9. Figure 10 is an excerpt from an information sheet to be included with NIST reports of calibration of saturated standard cells and solid-state voltage standards. The information sheet to accompany NIST reports of calibration of high precision resistance standards will contain a similar paragraph. However, as previously indicated, an ideal representation of the ohm based on the quantum Hall effect and R_{K-90} is expected to be consistent with the SI ohm to within an assigned relative one-standard-deviation uncertainty of 0.2 ppm (0.2 μΩ for a resistance of 1 Ω).

UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
[formerly National Bureau of Standards]
Gaithersburg, Maryland 20899

R E P O R T   O F   C A L I B R A T I O N

DC Voltage Standard

Description of Standard
Standard Cell Enclosure
Model .... S/N ....
Containing 4 Saturated Standard Cells

Submitted By: ....
....
....

This standard cell enclosure was received August 30, 1990, under power and at its normal operating temperature.

The values in the table below are based on the results of daily measurements of the differences between the emf's of the cells in this standard and those of NIST working standards calibrated in terms of the Josephson effect using the new conventional value of the Josephson constant internationally adopted for use starting on January 1, 1990, namely, K_{J-90} = 483 597.9 GHz/V exactly.* The measurements were made in the period from November 2, 1990 to November 17, 1990.

POSITION NUMBER	EMF (volts,V)	UNCERTAINTY (microvolts,μV)	EMF (volts,V)	UNCERTAINTY (microvolts,μV)
1	1.0181770	0.27	1.0181776	0.27
2	1.0181787	0.27	1.0181794	0.27
3	1.0181775	0.27	1.0181781	0.27
4	1.0181775	0.27	1.0181781	0.27

The electromotive forces on the left above were corrected to nominal temperature (30.0 degrees Celsius) using the International Temperature Formula proposed by F. A. Wolff. The electromotive forces on the right are at the mean operating temperature during the test (29.9887 degrees C) as determined by use of a temperature deviation measuring device mounted in the enclosure.

The above uncertainties include components for random fluctuations in the cell under test and in NIST equipment and standards, for a systematic error of 0.076 ppm in the measurements of NIST working standards in terms of the Josephson effect, and for the systematic error in transfer due to the finite resolution of the apparatus used to determine the temperature of the cells under test. In the case of standard cells tested in NIST oil baths, the latter uncertainty is replaced by the emf equivalent of 0.005 degrees Celsius which is the uncertainty of the

*For additional information, see NIST Technical Note 1263, "Guidelines for Implementing the new Representations of the Volt and Ohm Effective January 1, 1990," by N. B. Belecki, R. F. Dziuba, B. F. Field, and B. N. Taylor (June 1989).

Test No. ....

Fig. 9a. Example of a NIST calibration report for saturated standard cells, page 1.

Standard Cell Enclosure
Model .... S/N ....

temperature measurements in this laboratory. The random error component is computed from the standard deviation of the mean emf and is at the three sigma level.

These uncertainty figures contain no allowance for the effects of transportation upon this standard. The minimum uncertainty due to such effects under very carefully controlled transport conditions has been found to be 0.42 ppm (3 sigma). Any valid uncertainty statement applying to the above values when the standard has been moved from the NIST Volt Facility must contain such a component of error. If data from which to estimate the transport error are not available, one part per million is not an unreasonable value. Also not included in the above uncertainties is an allowance for long term drift of the values of the outputs of this standard. This must be determined from historical data on a case by case basis.

A summary and analysis of the data upon which the above values are based is appended. A complete explanation of the uncertainty statements given above as well as additional information regarding NIST calibration of such voltage standards is also included.

For The Director,
National Institute of Standards and Technology

Norman B. Belecki, Group Leader
Electricity Division

Test No. ....
Date: November 23, 1990

Fig. 9b. Example of a NIST calibration report for saturated standard cells, page 2.

As of January 1, 1990, the U.S. reference standard of voltage has been based on eq. (1) taking for the Josephson constant K_{J-90} = 483 597.9 GHz/V exactly. This value is that adopted by international agreement for implementation starting on January 1, 1990, by all national standards laboratories that base their national representation of the volt on the Josephson effect. Since all such laboratories are expected to use the same conventional value of the Josephson constant while prior to this date they did not, the significant differences which previously existed among the values of some national representations of the volt should no longer exist [4]. Moreover, the national standards laboratories of those countries that do not use the Josephson effect for this purpose are requested to maintain their own national representation of the volt to be consistent with the above conventional value of the Josephson constant, for example, through periodic comparisons with a laboratory that does use the Josephson effect. An ideal representation of the volt based on the Josephson effect and K_{J-90} is expected to be consistent with the volt as defined in the SI to within an assigned relative one-standard-deviation uncertainty of 0.4 ppm (0.41 µV for an emf of 1.018 V). Because this uncertainty is the same for all national standards laboratories and is not relevant for traceability to national standards, it is not included in the uncertainties given in NIST Reports of Calibration. However, its existence must be taken into account when the utmost consistency between electrical and nonelectrical measurements of the same physical quantity is required. (Examples are the electrical and mechanical measurement of power, and the electrical and thermal measurement of energy.)

Fig. 10. Excerpt from an information sheet to be included with NIST reports of calibration on saturated standard cells and solid-state voltage standards.

6. Adjustment of Instrumentation

It is important to follow manufacturers' instructions when making any adjustments to instrumentation. It must always be remembered that recommendations in this section are general guidelines only, not specific procedures. Following procedures and instructions specific to your instruments is the only sure way to avoid errors and problems.

6.1 Voltage Instrumentation

Calibrators and precision sources – Calibrators should be adjusted using a standard calibrated to be consistent with V(NIST–90). A standard in this context means any device with sufficient stability, resolution, and absense of noise to transfer the representation with an uncertainty smaller than the calibrator's smallest uncertainty by a factor of three or more. The adjustment to be made is generally that of the internal reference of the calibrator and such an adjustment affects all selectable output levels proportionally. For that reason it may be sufficient to perform the adjustment at one voltage level, say, ten-volts nominal. The adjustment would have the result of *increasing* the positive voltage output at any fixed setting by 9.264 ppm of prior value if the calibrator were perfect. However, no calibrator is perfect and one can safely assume that the change in output would differ from +9.264 ppm by some amount due to a combination of calibration errors and instrument drift since the last calibration. For purposes of verifying the adjustment, the manufacturer's accuracy and drift specifications or your own past calibration data on the calibrator may be used to estimate the extent of the difference likely to be obtained.

The adjustment may be checked by measuring one or two output levels on each voltage range with a digital voltmeter, of 6 1/2-digit resolution or better, immediately before and after the adjustment is made. The increase of voltage in proportional parts of each of the readings should be the same, taking into account the linearity specification of the calibrator.

For example, assume this was done, and the results appearing in Table III were obtained.

TABLE III
CALIBRATOR OUTPUTS BEFORE AND AFTER ADJUSTMENT

Range	Before Data	After Data	Δ (ppm)
10 Volt	10.00002	10.00010	8.0
	-10.00005	-10.00012	7.0
100 V	100.0003	100.0011	8.0
	-100.007	-100.0014	7.0
1000 V	1000.005	1000.014	9.0
	-1000.002	-1000.010	8.0

The proportional change in ppm was calculated using the equation:

$$\Delta = \frac{\text{After - Before}}{\text{Before}} \times 10^6.$$

Two observations can be made from these data. The first is that the differences Δ are consistent within the resolution of the meter used to obtain them. Inconsistenties would have indicated a possible procedural error in making the adjustment. The second is the differences have the correct sign and are of about the right magnitude. This indicates that most likely the adjustment has been made properly. If the differences were very far from 9 ppm, a recheck using an independent standard would be advisable. Note also that it is possible (but unlikely) that the effect of drift in the calibrator since its last calibration and an error in making the adjustment could cancel one another, leaving the impression that the adjustment was correctly performed.

Digital voltmeters and multimeters – The best way to perform the adjustment on a digital meter is to use a calibrator of appropriate accuracy to adjust its internal reference based on a nominal ten-volt input to the meter, thus following the same approach used in the case of calibrators. This will have the effect of *reducing* the reading obtained when measuring a fixed voltage before and after the adjustment. Accordingly, to ensure that the adjustment was properly made, one may simply measure one or two voltages on each range before and after the adjustment.

6.2 Resistance Instrumentation

Measurements of resistance at accuracy levels high enough to be affected by the change in the ohm representation are made only by a few of the highest resolution digital multimeters and perhaps one or two calibrator models. In the case of a digital multimeter, the measurement is usually made by measuring the voltage drop across the unknown resistance caused by a constant current produced by a source within the meter. In adjusting the meter, the current is physically adjusted or corrections stored while reading a sequence of standard resistors, typically one per range. Unlike the case of voltage adjustments, the 1.69 ppm change will be difficult to see as it is small relative to the resolution of even the best meters.

6.3 General Considerations Regarding Adjusting Instruments

6.3.1 Adjust instruments without using standards at your own risk

It is possible to bring instruments into compliance with the new representations in a technically-sound way without recourse to standards. However, such procedures are not recommended by the Ad Hoc Committee because of logistics problems they may create. As an example, consider the adjustment of a DVM. The adjustment can be done by connecting it to a stable ten-volt source, noting the DVM reading, computing what the reading should be after the change, and adjusting the reference circuit of the DVM to obtain the new reading. Even though this would permit the adjustment of the DVM *in situ*, without involving standards, *it is not a preferred procedure because of the risks involved.* Unless you are careful to mark the DVM somehow, e.g., with the logo described in sec. 2.2.4, the danger exists that it could be adjusted more than once and therefore have an offset large enough to put it outside of its specifications. It should also be recognized that the above procedure is illustrative only. Other pitfalls possibly encountered in this approach include:

- High likelihood of making mathematical errors in calculating the adjusted reading.
- Overlooking the existence of a second internal reference in, for example, dual-slope integrating voltmeters.
- Failing to compensate for zero offsets.
- Failing to understand that any error existing in the instrument prior to the adjustment is propagated unaltered through the adjustment under this procedure, i.e., the procedure has none of the aspects of a calibration.

If you insist on adjusting instruments without using standards, *it is imperative that the manufacturers' adjustment procedures be taken into account.*

6.3.2 Where should the adjustments be made?

Since complete recalibrations are not necessary to bring meters and sources into compliance with the changes (see sec. 2.2.1), it is possibile to make the adjustments at the user's site. This is ideal for it would enable the change at the user level to be made quickly, allowing compatibility of measurements in a large production or quality-assurance system to be maintained readily. It also enhances the value of the measurement results from instruments so adjusted because the adjustment is made under use conditions, thus eliminating the effects of differences between the environments of the calibration laboratory and the user's site. In many cases this difference can be extreme; in the calibration laboratory, the instrument is calibrated on a bench top, but when in use it will likely be in a rack with other heat-generating equipment.

Most modern voltmeters and calibrators whose accuracies are high enough that they will be affected by these changes are "smart" instruments. That is, they contain microprocessors for control and operational purposes. Most also contain non-volatile memory used to store calibration corrections. The references of these can be adjusted by using a procedure based on the idea of measuring a source and then "telling" the instrument its value. The meter then computes and stores a new value for its own reference. The simplicity of this makes *in situ* adjustment feasible. However, the adjustment should be done only with a source calibrated to sufficient accuracy and a logo or label should be used to indicate that an adjustment has been made.

Digital instruments and precision sources of older design — i.e., those not using microprocessors for operation and control, will require manual adjustment of reference outputs. Because of this, the feasibility of making the required adjustments at the user's site is diminished. For such cases, the decision whether to pull the instrument out of service merely for adjustment or to perform a complete calibration depends on the circumstances. Since adjusting references of instruments is not a particularly time-consuming task, it may be worthwhile to dedicate a technician and work station to do nothing but adjust test equipment voltage and resistance references. This will guarantee that instruments are not taken out of service for an inordinate time and that the calibration laboratory work schedule is not artificially perturbed by the changes.

There will undoubtedly be digital instruments, and perhaps even standards, for which the range of adjustment is insufficient to permit the entire change to be made. In such cases, circuit modifications may be necessary. The manufacturer of the instrument should be consulted prior to making such alterations. In the case of standards, good practice suggests that no physical adjustments be made to them. Rather, a record of their values, both recent and historical, should be maintained and used to determine a "best" current value. That is, standards should *not* be physically adjusted to their new nominal values; any changes should be in record keeping only.

Many instruments affected by these changes are embedded in computer-controlled test or measurement systems. Where such instruments serve as the reference standards for the system, the adjustments should be made as soon as practical if the system is required to make measurements with uncertainties of 100 ppm or smaller. The system itself should be self-calibrated immediately after the adjustment is made to the reference standard. Data from the self-calibration should be compared with data from previous self-calibrations to ascertain that the adjustments have been properly made. If there is any question, a separate calibrated standard should be used to check the system as a whole.

In principle, adjustments for the changes could be made in the system software. This is not good practice for cases where a precision digital multimeter or programmable source or calibrator is used as a standard for the system. In addition to the possibility of creating blunders in the system software, this approach creates a problem if the instruments involved have to be replaced for maintenance or other reasons. It is far better to make the adjustments to the instruments themselves. In cases where a precision analog-to-digital converter (ADC) or digital-to-analog converter (DAC) is used as the primary reference for a system, corrections are generally stored in the system software. These corrections must be sought out and altered.

All adjustments should be thoroughly documented. If shifts in test results appear, or are likely to appear, because of the adjustments, notification should be given to those affected so that they can determine if their process has gone out of control.

7. Other Quantities

7.1 Direct Current

Since A = V/Ω, where A is the SI ampere, the U.S. representation of the ampere will increase by +7.57 ppm. The new representation will be consistent with the SI ampere to within 0.45 ppm (1σ). However, no standards of direct current *per se* are kept at NIST or at any other national standards laboratory. Known currents for calibrating current sources, ammeters, or the current function of digital multimeters are established using resistance and voltage standards, the treatment of which is covered in secs. 3 and 4 above. According to the criteria in sec. 2.1, only meters and sources capable of measuring or producing currents at the 80 ppm level of accuracy or better need be considered for adjustment.

7.2 Alternating Voltage and Current

All measurements of ac voltage and current, including calibrations of ac calibrators and the ac function of digital multimeters, are affected by the changes in the volt and ohm representations since they are based on dc standards. The magnitude of the change is the same as that for a dc measurement of the same quantity.

Calibrations of ac instrumentation of the highest accuracy are based on the use of dc standards and thermal transfer standards (thermal voltage and current converters). The latter have a calibrated and nearly flat frequency response. They are used to compare rms ac signal levels with nearly equal dc levels produced or measured by dc standards. The uncertainty at any calibration point is a function of the uncertainty of the dc standard and that of the ac-dc difference of the transfer standard at that frequency and voltage or current level. At frequencies above 20 kHz, the uncertainty associated with the transfer standard may dominate, increasing from a possible low of a few ppm in the audio frequency range to hundreds of ppm at frequencies above 100 kHz [17].

The ac-dc differences of thermal converters are not affected by the change in the unit representations. They depend on the materials and geometry of the thermal converters and are determined ultimately on theoretical grounds at NIST and other national standards laboratories.

AC calibrators make the routine calibration of the ac functions of large numbers of digital multimeters feasible. Such calibrators are precision adjustable sources, usually programmable, which supply very pure sine waves whose amplitude and frequency may be selected with a precision of one ppm or better. They are calibrated using thermal voltage converters and a dc voltage calibrator. The uncertainty of the calibration at each point is limited by the stability of the source itself, the dc calibrator, and the uncertainties of the thermal converters. The very same considerations apply to the adjustment of an ac calibrator as to a dc calibrator. The adjustment need only be made at one point since the level of the internal reference is what will be adjusted; see sec. 6.1.

Digital multimeters generally make use of an rms-responding thermal converter, a log-antilog converter, or sampling techniques to make ac voltage measurements. In the first two cases, the converter produces a dc voltage which is measured by the dc voltmeter. In the third, the waveform is sampled repeatedly, dc measurements are made of the samples, and the rms value of the waveform is calculated by a microprocessor in the meter and displayed. The calibration technique for each case is the same, namely, to supply a known voltage at a known frequency from an ac calibrator and thereby determine the error of the meter. (Present meters simply have no facility for independent analysis of the converter circuit.) Since a conversion to dc is made and a dc voltage measured to determine the ac voltage, the adjustment of the dc function — by adjusting its reference — should be sufficient for ac as well. However, the manufacturer's instructions should be checked to be sure. As in the case of a dc meter, the measurement of a fixed voltage just after the adjustment is made should result in a lower value than that from a measurement of the same voltage immediately prior to the adjustment.

The same accuracy levels apply to ac quantities as to dc quantities for determining if adjustments for the new representations are to be made. The only differences in the two situations are that for ac the accuracy depends on the frequency as well as the amplitude, and that the accuracy levels are considerably lower because of the performance limitations of the con-

verters or sampling schemes used. Therefore, far fewer ac instruments will be affected than dc instruments.

7.3 Capacitance and Inductance

A calculable cross-capacitor is used at NIST to realize the SI farad. The results of such realizations in 1961 and 1974 were used to determine the mean value of the group of 10-picofarad, fused-silica capacitance standards which maintain the U.S. farad representation. All calibrations of capacitance standards at NIST are ultimately based on this mean value.

The most recent realizations (1988) of the SI farad at NIST indicate that the current NIST farad representation exceeds the SI farad by approximately 0.14 ppm [18]. (This is a preliminary figure as further measurements will be carried out during 1989.) Thus, on January 1, 1990, the U.S. farad representation will be reduced by approximately 0.14 ppm.[4]

In keeping with the previously-expressed rule delineating the accuracy levels over which the change has impact, no capacitors whose calibration uncertainty exceeds 2 ppm should be affected. This limits the impact to the calibration of fused-silica dielectric standard capacitors for which the range of calibration uncertainties falls between 0.5 and 1.5 ppm. For these, the adjustment must be made.

Note that, unlike V(NBS–72) and Ω(NBS–48)$_t$, the U.S. farad representation is too large and will be decreased. *This means that assigned values of standard capacitors must be increased by 0.14 ppm of nominal value if the last calibrated value is used as the current value.* If the calibration history of the capacitor is used to produce a curve from which daily values of the standard are projected, the curve must be translated up by 0.14 ppm or the scale of the *y*-axis changed appropriately (see secs. 3.4 and 4.3).

The U.S. representation of the henry is realized via a Maxwell-Wien bridge as the product of the values of two resistors and a capacitor. In principle, therefore, it should change by about (1.69 + 1.69 - 0.14) ppm or 3.24 ppm. However, because the lowest uncertainty currently given for NIST calibrations of standard inductors is 200 ppm, a change of 3.24 ppm will have no practical effect on values of inductance. Therefore no adjustment is necessary.

7.4 Power and Energy

The SI unit of power, the watt, is related to the volt and ohm by the equation:

$$W = V^2/\Omega .$$

The U.S. electrical representation of the watt therefore will increase by 16.84 ppm and will be consistent with the SI watt to within 0.83 ppm (1σ). The U.S. electrical representation of the unit of energy, the watthour, will also increase by the same fraction.

A calibration of a wattmeter produces a correction or corrections to be applied to its readings to obtain the correct value. To comply with the change in the watt representation, *the correction must be made more negative by 16.84 ppm.* Such corrections should be made as soon after January 1, 1990, as is feasible for all wattmeters used at the 85 ppm level of accuracy or better. No adjustment is necessary to the corrections of meters with accuracies of 170 ppm or greater. Meters whose accuracies are between 85 and 170 ppm fall into a "gray" area where a decision to adjust must be based on the criticality of the application, the time remaining before the next scheduled recalibration, and other such factors [19].

Watthour meter calibration results are expressed in terms of "percent registration." For example, if a watthour meter spins too fast (indicates an erroneously higher level of energy) by 0.1%, the reported value is 100.1% registration. In order to comply with the change in the watt representation, the percent registration value for a given meter should be decreased by 16.84 ppm (0.001 684%). The guidelines given in the paragraph above should be used to determine the cases for which an adjustment is appropriate [20].

It is expected that only the most accurate wattmeters and watthour meters will be affected by the change. These are primarily standards and development prototypes for use at power frequencies. Most power measurements made at other, higher frequencies are of sufficiently low accuracy that they should not be affected. In some cases, measurements of transformer loss are made at a sufficient level of accuracy that the adjustment should be made.

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[4] The new NIST representation of the farad will be very close to the SI farad. The uncertainty of a realization is of the order of ±0.015 ppm (1σ). Because of the intrinsic coherence of the SI system, the NIST representation of the farad will be consistent with those of the volt and ohm to well within the latter's assigned uncertainties.

8. Transducers

Transducers and sensors designed to allow the measurement of non-electrical quantities by electrical means generally fall in the accuracy range from 0.05% (500 ppm) to 0.5% [21]. Those few having higher accuracies, such as load cells and platinum resistance thermometers, quantify the measurand in terms of a ratio of electrical quantities and therefore are unit independent. Accordingly, changes in values of electrical standards should not create any technical problems.

However, in the case of a standard platinum resistance thermometer (SPRT), a small error could arise if proper practices are not followed. An SPRT measures temperature via the ratio of its resistance at the temperature to be measured, R_t, to that at 0°C, R_0. R_0 should be determined frequently as a check on both the SPRT and the measuring instrumentation as a matter of good practice. A redetermination of R_0 must be made at the time of adjusting instrumentation to comply with Ω(NIST–90) to avoid introducing a 1.69 ppm error into the ratio R_t/R_0. (Alternatively, the value of R_0 can be reduced by 1.69 ppm.) The error caused by failing to redetermine (or adjust) R_0 is small for practical purposes, approximately -0.5 mK at room temperature, but could be significant for the most precise temperature measurements.

For further information on temperature measurements and the definition of the new 1990 temperature scale, see *Guidelines for Realizing the International Temperature Scale of 1990 (ITS–90)* [16].

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Appendix 1

Membership of the NCSL Ad Hoc Committee 91.4
"Changes in the Volt and Ohm"

	A. Anderson	Guildline Instruments
	L. Auxier	Beckman Instruments
	B. Barnaby	Sandia National Laboratories
	B. Belanger	NIST
Chairman	N. Belecki	NIST
	B. Bell	NIST
	D. Braudaway	Sandia National Laboratories
	S. Brodecki	GTE
	B. Bruce	Hewlett-Packard
	M. Cheniae	Defense Logistics Agency
	R. Cohen	Rockwell International
	D. Collins	GTE
	J. Corege	Hewlett-Packard
	D. Dalton	John Fluke Manufacturing Co.
	G. Davidson	TRW Electronics & Defense Sector
	A. Domenichini, Jr.	Defense Logistics Agency
	R. Dziuba	NIST
	A. Ehman	Beckman Instruments
	W. Eicke	Self
	B. Einstein	Northrop Corporation
	B. Field	NIST
	F. Flynn	USAF Directorate of Metrology
	R. Geesaman	Hughes Aircraft Co.
Secretary	R. Goff	Rockwell International
	J. Hirning	John Fluke Manufacturing Co.
	S. Howie	U.S. Naval Air Test Center
	L. Huntley	John Fluke Manufacturing Co.

Appendix 1 (continued)

Membership of the NCSL Ad Hoc Committee 91.4
"Changes in the Volt and Ohm"

	K. Jaeger	Lockheed Missiles & Space Co
Publicity	C. Johnston	Self
	F. Katzmann	Ballantine Laboratories
	F. Kern	NASA Langley Research Center
	E. Kifer	Keithley Instruments
	R. Kletke	John Fluke Manufacturing Co.
	Y. Komorita	TRW Electronics & Defense Sector
	J. MacKinnon	U.S. Navy Western Standards Laboratory
	D. Mednick	Hq. Army Materiel Command
	B. Moore	U.S. Army TMDE Support Group
	T. Mukaihata	Hughes Aircraft Co.
Publicity	E. Nemeroff	Self
	N. Oldham	NIST
	O. Petersons	NIST
	J. Ramboz	NIST
	R. Robertson	Guildline Instruments
	R. Semer	USAF Directorate of Metrology
	M. Shaw	Guildline Instruments
	C. Sides	Boeing Aerospace Co.
	A. Smith	U.S. Naval Air Test Center
	S. Staley	Datron Instruments
	B. Taylor	NIST
	G. Trinite, Jr.	U.S. Navy Metrology Engineering Division
	A. Van Couvering	Hughes Aircraft Co.
	J. Wehrmeyer	Eastman Kodak
	B. Wood	National Research Council of Canada
	D. Workman	Martin Marietta Aerospace

Appendix 2

Concerns of NCSL Ad Hoc Committee 91.4 about Logistics and Management Issues Stemming from Changes in the Unit Representations

A. Introduction

The information given in the earlier portions of these *Guidelines* deals primarily with adjustments to single standards, small groups of standards, or individual instruments to bring them into compliance with the new unit representations. This appendix summarizes the discussions and concerns of NCSL Ad Hoc Committee 91.4 about problems created in propagating the changes through a large population of instruments or test equipment, i.e., logistics and management issues.

Implementing the changes among such populations can create both technical and management problems since it may seriously affect calibration laboratory operations, test equipment management, and quality-assurance activities in production areas. This is especially probable if the metrology department supports a large number of particularly accurate instruments or the manufacture of exceptionally precise products. The most obvious and likely of these problems are discussed in the ensuing paragraphs to bring them to the attention of readers. Solutions cannot be provided since the problems are very strongly situation-specific.

Nonetheless, it should be noted that the chance of technical problems arising in the manufacture of products other than precision voltmeters and dc calibrators due to the changes is exceedingly small unless gross blunders are made. Measurements performed in direct support of production usually have tolerances much larger in magnitude than those of the changes. On the other hand, those technical problems which will come into being might well be insidious rather than glaring.

B. Technical and Logistics Problems

The problems to be discussed stem from three basic causes: (1) adjustments cannot be made simultaneously throughout the entire population of standards and test equipment; (2) specified values of quantities dependent upon electrical units and thus possibly requiring adjustment are imbedded in procedures, software, designs and blueprints, and in some cases firmware; and (3) residual product manufactured in terms of the pre-1990 electrical representations will remain on the shelf until long after January 1, 1990, and perhaps long after new values are incorporated into designs.

B.1 "Coexistence"

The changes will propagate throughout the National Measurement System beginning January 1, 1990. The sheer volume of instrumentation affected ensures the existence of a transition period during which the new and pre-January 1, 1990, representations will coexist within the System. The duration of this coexistence may be, in the extreme, as long as two years because of the length of recalibration intervals.

Incompatible products or components — As a result of the old and new unit representations coexisting, components or sub-assemblies manufactured to a tight tolerance in one place could be out of tolerance at the next step in the manufacturing process if the adjustments are not coordinated. This is especially likely if they are manufactured by a facility or company in one location for use in a different location, such as in contractor/sub-contractor situations. If this were to happen in a situation where sufficient testing is done and the discrepancy is recognized immediately by people who are aware of the changes, the cost would be minimal. On the other hand, if the parts or subassemblies are accepted as good and the discrepancy is sufficiently large as to cause an operational or performance problem in the long term, the costs could be high.

Effect on instrument manufacturing — One could conceive of a situation in which a failure to coordinate properly the change in the volt representation could result in the production of an instrument whose range of adjustment is offset sufficiently that it could no longer be brought within tolerance after a few calibration cycles. The drawbacks of this are apparent: the manufacturer might have to provide modifications to fix instruments already sold (costly) and the company would certainly have tarnished their reputation. Moreover, the cause of the problem might well be (mis)perceived as a design failure by the manufac-

turer, thereby creating a large additional expense, or premature withdrawal of the product.

Coordination needed — The transition will only occur smoothly and without incident if standards and calibration laboratories, the test equipment management organization, the quality-assurance staff, and the ultimate users of the test instruments and of the data they produce cooperate to identify those situations in which the coexistence of two values of the same parameter creates a problem and act in concert to restandardize.[1] *All* individuals involved in the use and servicing of the test equipment or instrumentation must be kept informed about the changes and the plans for implementing them. Coordination of the changes within a single company will not be easy; coordination of the changes between two companies with a supplier-user relationship will require careful planning and extensive communication.

Calibration workload control — One of the first problems expected will surely come from partially informed or misinformed users. Users convinced that the changes call for the complete recalibration of all instrumentation will inundate the calibration laboratory with requests for service, demanding that everything be recalibrated early in January. Of course this is impossible, and in most cases it is probably not necessary. *Users must be informed, not only of the fact of the changes, but of the likely impact (or lack thereof) as well.*

It will require extra effort on the part of the calibration laboratory and equipment management organization to ensure that adjustments are made promptly to instrumentation where the measurements required are both critical and of high accuracy. It is advisable to perform adjustments (as described in these *Guidelines*) rather than complete recalibrations to avoid rearranging the workload pattern of the calibration laboratory and creating repeated peak workload levels in the future. Such a condition can cause scheduling problems, overtime, and extra work long after the technical effects of the changes are past.

Production support — Care must be taken that the order in which test equipment is adjusted does not adversely affect production or quality. There are products, such as high-accuracy instrumentation, precision components, and guidance systems, whose successful manufacture depends on compatibility of results of measurements made by an ensemble of instruments, perhaps in use in a number of locations or organizations within a company. The coordination of restandardization in such a situation is very important. It must be decided whether to adjust all instrumentation at the same time or to adjust a critical subset of instruments simultaneously and proceed with the remainder at a more leisurely pace. The former course of action may be desirable if only to avoid possible confusion. The effect of adjusting instrumentation providing data for control charts used to monitor production processes must be thought out carefully. To carry out restandardization in either case, the full cooperation of the quality-assurance staff is necessary since a thorough understanding of all of the quality aspects of the system is required.

Stability test support — There is one obvious circumstance in which a delay in making the changes should be considered. In the case where components or assemblies are in the process of stability testing, the instrumentation used to perform the test should not be adjusted until the conclusion of the test. If the same instrumentation is used to perform stability measurements on groups of items whose test durations overlap, it is preferable to interrupt the test sequence at the end of the test of a particular group, adjust the instrumentation, and begin testing afresh. This precludes any possible mix-up in the results of testing. If instrumentation must be adjusted during the course of a stability test due to a need to maintain a high rate of testing, the resulting data sets will contain offsets. There are two ways of dealing with such effects.

The first is to cope with the offset during the analysis of the data. For limited sets of data this may require that those data points which include an offset due to the adjustment be analyzed by a person rather than a 'canned' computer program to avoid modifying data analysis software. For larger data sets, it may appear more feasible to build correction routines into the analysis software. However, the problem may be complicated by naturally occurring changes in the measurement instruments and the methods by which corrections for such changes are applied to the data.

The second is to build a correction routine into the data acquisition software. This is not recommended because it is generally poor practice to store corrected data. If blunders in applying corrections are made from the beginning, reconstruction of the raw data can become very difficult, if not impossible.

[1] The term "recalibration" refers to the verification and adjustment (if necessary) of all ranges and functions of an instrument to ensure its compliance with specifications; "adjustment" or "restandardization" refers to a limited set of actions, such as adjustment of the voltage reference alone in a digital voltmeter, intended to bring the instrument into compliance with the new unit representations.

B.2 "Embedded" Values

A potential source of trouble exists wherever voltage values (or in rare cases resistance values) are explicitly called out in written procedures, embedded in software, or called out in design specifications. Whether a problem exists, and if so, how severe it is, depends on the nature of the application and, of course, the level of accuracy required. There are generally two types of situations. The first is where the procedure or software is being used to quantify a transfer function. In such cases one measures the response of the circuit or device to a stimulus. This process is in actuality a ratio determination and independent of units. Therefore no alteration needs to be made to the values specified in the procedure or software. The calibration procedure for an instrument is a specific example of this. It describes how one determines a transfer function, i.e., the instrument's response to a known input. The table below is typical of what might be found in a procedure for calibrating a meter. It gives the range of values to within which the meter must be adjusted for a given input.

Input	Adjust reading to be within
1.000 000 V	0.999 990 V to 1.000 010 V
5.000 000 V	4.999 990 V to 5.000 010 V
10.000 00 V	9.999 900 V to 10.000 10 V

Clearly, the ratio of the reading to the input is independent of units and therefore not affected by any change in the volt representation.

In the second type of situation, alteration of the values specified in the procedure or software is required. Such is the case where, to function properly, a device requires a specified value in a given set of units for a particular parameter. An example of this is the specification of alignment parameters for an inertial guidance system based on gyroscopes or integrating pendula. The electrical specifications here are driven by the physics of the guidance system. Levels of current produced are set by inertial responses to changes in velocity. These levels will not change (they are like fixed-value standards in a sense) and therefore the specified voltage and resistance values must be adjusted to reflect the changes in the unit representations to avoid the possibility of malfunction.

This raises the issue of what must be done when one must maintain devices of the same model manufactured before and after January 1, 1990. The situation will be confusing since alignment instructions will be different for the two cases.

It must be stressed that there are very few instances where accuracy requirements are such that specified values in procedures, software, etc., will create a problem — the real problem will be in mounting the effort required to identify where adjustments are necessary.

B.3 Residual Product

Problems may be expected to be caused by the existence in inventory of residual product manufactured in terms of the pre-1990 unit representations. This could happen at several levels: for components or sub-assemblies to be used in manufacturing (but relatively rarely because of the level of accuracy involved); standards guaranteed to be within a narrow tolerance; instruments such as voltmeters and calibrators; and systems ordered by the Department of Defense (DoD), such as guidance systems. Presumably the number of such problems will be small since one would expect that such items would be carefully measured or, in the case of components, circuits adjusted before use. This should have the effect of making the problem a calibration problem. Again, the only solution for these problems is a well-informed technical community. If those involved are aware of the changes, they will take action to avoid the few problems which are likely to arise.

C. Contractual or "Legal" Problems

The problem areas mentioned above are technical in nature; that is, they could readily result in malfunctioning equipment, erroneous measurement results, or the manufacture of unacceptable product. There is yet another class of potential problems that could stem from contractual obligations for measurement traceability[2] required of suppliers of technological goods by the Department of Defense, NASA, and other government agencies; licensees of nuclear power stations by the Nuclear Regulatory Commission; and manufacturers of medical devices by the Food and Drug Administration. These requirements,

[2] Traceability refers to the requirement that all measurement instruments be calibrated (periodically) and that all calibrations performed be traceable to national standards, fundamental physical constants, or agreed-upon standards where neither of the former two exist. That is, an unbroken chain of documentation in the form of calibration reports referring to other reports of calibration of the instruments and standards used, etc., showing the linkages back to these basic starting points, must exist for each calibration.

set forth in DoD MILSTD 45662A and its predecessors, and similar documents of other agencies, have spawned a system of inspectors and audits which pervades commerce.

In a strictly legal sense, the magnitudes of the 'practical electrical units' in the United States will change on January 1, 1990. As noted previously, however, all measurement equipment affected cannot possibly be adjusted instantaneously and for some time after January 1, 1990, a fraction of the population of instruments will remain calibrated in terms of the pre-January 1, 1990, unit representations. This cannot be avoided unless the number of instruments in a location is exceedingly small. Fortunately, the changes are sufficiently small that only a very few of the processes supported by calibrated instruments will be noticeably affected technically. Nonetheless, auditors and inspectors will no doubt take the changes very seriously.

Accordingly, a plan for implementing the changes — complete with a rationale for continuing to use instrumentation not yet adjusted — should be developed and documented. This is compatible with the general philosophy behind MILSTD 45662A. The DoD does not want to dictate the details of how to run a calibration system, but rather to describe minimum requirements and permit their contractors and sub-contractors to deal effectively with the particulars of each situation. Control is through the requirement to document and to follow the documentation.

The following are elements which should be taken into consideration in developing a plan:

1. Adjustment of standards according to these *Guidelines*.
2. Identification of critical measurement requirements.
3. Coordination of the adjustment (or recalibration if appropriate) of instrumentation supporting critical measurements identified in the element above.
4. Adjustment of all other instrumentation whose specified accuracies are within 5 times the changes in the unit representations.
5. Identification of instruments with accuracies from 5 to 10 times the changes.
6. Identification of adjustment needs among these and scheduling their adjustment.
7. Coordination of all of the above among standards laboratories, calibration laboratories, test equipment management, and users.
8. Calibration report formats.
9. Use of labels, including those bearing the NCSL 'change logo' (see Fig.1, page 6).
10. Effect adjustments to standards and instruments will have on calibration intervals, and hence on workload cycles.
11. Effect adjustments will have on normal procedures for reporting out-of-tolerance conditions to users.
12. Education of users of test equipment *and users of the resulting measurement data* about the changes and their likely impact.

Appendix 3

Reprints

We wish to thank Springer-Verlag for allowing us to reprint the article by T. J. Quinn which appeared in *Metrologia*, Vol. 26, No. 1 (1989). *Metrologia*, the International Journal of Scientific Metrology, is published four times a year under the auspices of the International Committee of Weights and Measures. *Metrologia* publishes articles that are written by, and which constitute an important exchange of information among, the world's experts in the science of measurement. Many of these contributions are concerned with the significant improvement of fundamental measurements in the various fields of physics, notably the improvement of accuracy and precision in measuring length, mass, time, electrical current, temperature, luminance, and ionizing radiation, and the accurate determination of physical constants involved in such measurements. Periodically, *Metrologia* publishes invited review articles covering various fields of measurement, reports on international conferences of metrological significance, and summaries of relevant research and development programs under way in the major national standards laboratories. Its principal fields of interest are the improvement of basic measurements in physics; improved realizations of SI units; new values for the fundamental constants; international comparisons of standards; and innovative metrology in general, including articles that report new methods or improvements to existing methods that contribute in a significant way to the making of secondary measurements. Subscription inquiries may be directed to Springer-Verlag New York Inc., Service Center Secaucus, 44 Hartz Way, Secaucus, NJ 07094.

Special Report on Electrical Standards

New Internationally Adopted Reference Standards of Voltage and Resistance

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This report provides the background for and summarizes the main results of the 18th meeting of the Consultative Committee on Electricity (CCE) of the International Committee of Weights and Measures (CIPM) held in September 1988. Also included are the most important implications of these results. The principal recommendations originating from the meeting, which were subsequently adopted by the CIPM, establish new international reference standards of voltage and resistance based on the Josephson effect and the quantum Hall effect, respectively. The new standards, which are to come into effect starting January 1, 1990, will result in improved uniformity of electrical measurements worldwide and their consistency with the International System of Units or SI. To implement the CIPM recommendations in the U.S. requires that, on January 1, 1990, the value of the U.S. representation of the volt be increased by about 9.26 parts per million (ppm) and the value of the U.S. representation of the ohm be increased by about 1.69 ppm. The resulting increases in the U.S. representations of the ampere and watt will be about 7.57 ppm and 16.84 ppm, respectively. The CCE also recommended a particular method, affirmed by the CIPM, of reporting calibration results obtained with the new reference standards that is to be used by all national standards laboratories.

Key words: CCE; CIPM; Consultative Committee on Electricity; International Committee of Weights and Measures; International System of Units; Josephson effect; Josephson frequency-to-voltage quotient; ohm; quantum Hall effect; quantized Hall resistance; SI; volt.

Accepted: December 7, 1988

1. Background

The 18th meeting of the Consultative Committee on Electricity (CCE) of the International Committee of Weights and Measures (CIPM) was held September 27 and 28, 1988, at the International Bureau of Weights and Measures (BIPM), which is located in Sèvres (a suburb of Paris), France. NIST Director E. Ambler, a member of the CIPM and President of the CCE, chaired the meeting and the author attended as NIST representative. Some 30 individuals from 15 countries participated.

As discussed in this journal in the author's 1987 report on the 17th meeting of the CCE held at the BIPM in September 1986 [1], the CCE is one of eight CIPM Consultative Committees which together cover most of the areas of basic metrology. These Committees give advice to the CIPM on matters referred to them. They may, for example, form "Working Groups" to study special subjects and make specific proposals to the CIPM concerning changes in laboratory reference standards and in the definitions of units. As organizational entities of the Treaty of the Meter, one of the responsibilities of the Consultative Committees is to ensure the propagation and improvement of the International System of Units or SI, the unit system used throughout the world. The SI serves as a basis for

the promotion of long-term, worldwide uniformity of measurements which is of considerable importance to science, commerce, and industry.

However, scientific, commercial, and industrial requirements for the long-term repeatability and worldwide consistency of voltage and resistance measurements often exceed the accuracy with which the SI units for such measurements, the volt[1] and the ohm, can be readily realized. To meet these severe demands, it is necessary to establish representations[1] of the volt and ohm that have a long-term reproducibility and constancy superior to the present direct realizations of the SI units themselves.

Indeed, as discussed by the author in reference [1], in 1972 the CCE suggested that the national standards laboratories adopt 483 594 GHz/V exactly as a conventional value of the Josephson frequency-to-voltage quotient for use in maintaining an accurate and reproducible representation of the volt by means of the Josephson effect. While most national laboratories did adopt this value, three decided to use different values. Moreover, it has become apparent that the CCE's 1972 value of this quotient is about 8 parts per million (ppm) smaller than the SI value, implying that representations of the volt based on the 1972 value are actually about 8 ppm smaller than the volt.

It has also become apparent that because most national standards laboratories base their representation of the ohm on the mean resistance of a particular group of wire-wound resistors, the various national representations of the ohm differ significantly from each other and the ohm, and some are drifting excessively. Although the Thompson-Lampard calculable capacitor can be used to realize the ohm with an uncertainty[2] of less than 0.1 ppm, it is a difficult experiment to perform routinely. Hence, the 1980 discovery of the quantum Hall effect (QHE) by K. von Klitzing [6] was enthusiastically welcomed by electrical metrologists because it promised to provide a method for basing a representation of the ohm on invariant fundamental constants in direct analogy with the Josephson effect. The QHE clearly had the potential of eliminating in a relatively straightforward way the problems of nonuniformity of national representations of the ohm, their variation in time, and their inconsistency with the SI.

To address the problems associated with current national representations of the volt and ohm as discussed above, the CCE at its 17th meeting established through Declaration E1 (1986),[3] "Concerning the Josephson effect for maintaining the representation of the volt," the CCE Working Group on the Josephson Effect. The CCE charged the Working Group to propose a new value of the Josephson frequency-to-voltage quotient consistent with the SI value based upon all relevant data that became available by June 15, 1988. Similarly, recognizing the rapid advances made in understanding the QHE since its comparatively recent discovery, the CCE established through Declaration E2 (1986),[3] "Concerning the quantum Hall effect for maintaining a representation of the ohm," the Working Group on the Quantum Hall Effect. The CCE charged the Working Group to (i) propose to the CCE, based upon all relevant data that became available by June 15, 1988, a value of the quantized Hall resistance consistent with the SI value for use in maintaining an accurate and stable national representation of the ohm by means of the QHE; and (ii) develop detailed guidelines for the proper use of the QHE to realize reliably such a representation.[4]

Further, the CCE stated its intention to hold its 18th meeting in September 1988 with a view to recommending that both the proposed new value of the Josephson frequency-to-voltage quotient and the proposed value of the quantized Hall resistance come into effect on January 1, 1990. These values would be used by all those national standards

[1] The volt is the SI unit of electromotive force (emf) and electric potential difference. Occasionally it may be referred to in the literature as the absolute volt. As-maintained volt, representation of the volt, laboratory representation of the volt, "national unit of voltage", "laboratory unit of voltage", "practical realization of the volt", and other similar terms are commonly used to indicate a "practical unit" for expressing measurement results. However, to avoid possible misunderstanding, it is best not to use the word *unit* in this context. The only unit of emf in the SI is, of course, the volt. In keeping with references [2] and [3], from which this report has drawn heavily, we use the expression *representation of the volt* and variations thereof. The expression *reference standard of voltage* is also used occasionally in a similar or related sense. The situation for the ohm and resistance is strictly analogous.

[2] Throughout, all uncertainties are meant to correspond to one standard deviation estimates in keeping with CIPM Recommendation 1 (CI-1986) [4,5].

[3] The complete declaration is given in reference [1], but see also references [5] and [7].

[4] The members of the CCE Working Group on the Josephson Effect were R. Kaarls, Van Swinden Laboratorium (VSL), The Netherlands; B. P. Kibble, National Physical Laboratory (NPL), U.K.; B. N. Taylor, (NIST); and T. J. Witt, Coordinator (BIPM). The members of the CCE Working Group on the Quantum Hall Effect were F. Delahaye (BIPM); T. Endo, Electrotechnical Laboratory (ETL), Japan; O. C. Jones (NPL); V. Kose, Physikalisch-Technische Bundesanstalt (PTB), F. R. G.; B. N. Taylor, Coordinator (NIST); and B. M. Wood, National Research Council of Canada (NRCC), Canada.

laboratories (and others) that base their representation of the volt on the Josephson effect, and that choose to base their representation of the ohm on the QHE. These proposals of the CCE were subsequently approved by the CIPM [8] and by the General Conference of Weights and Measures (CGPM) [9] under whose authority the CIPM functions.

In response to the CCE's directives, each Working Group prepared a report which focused on the review and analysis of the values of the Josephson frequency-to-voltage quotient or quantized Hall resistance in SI units that were available by June 15, 1988; and the derivation of a recommended value for the purpose of establishing an accurate and internationally uniform representation of the volt and of the ohm based on the Josephson effect and on the quantum Hall effect, respectively. Submitted to the CCE in August 1988, the reports include useful background information as well as a discussion as to how the new representations might be used in practice to express calibration results. In keeping with the CCE's charge, the QHE Working Group also prepared a companion report entitled "Technical Guidelines for the Reliable Measurement of the Quantized Hall Resistance." Because unbiased quantized Hall resistance determinations are required for an accurate and reproducible representation of the ohm based on the QHE, these guidelines are of exceptional importance.[5]

2. CCE 18th Meeting Discussion and Principal Decisions

As an aid to the reader, this section of the report also includes some tutorial information.

2.1 Josephson Effect

2.1.1 Definition of Josephson Constant When a Josephson junction is irradiated with microwave radiation of frequency f, its current vs voltage curve exhibits steps at highly precise quantized Josephson voltages U_J. The voltage of the nth step $U_J(n)$, n an integer, is related to the frequency of the radiation by

$$U_J(n)=nf/K_J, \tag{1}$$

where K_J is commonly termed the Josephson frequency-to-voltage quotient [11]. The Working Group on the Josephson Effect (WGJE) proposed that this quotient be referred to as the Josephson constant and, since no symbol had yet been adopted for it, that it be denoted by K_J. It follows from eq (1) that the Josephson constant is equal to the frequency-to-voltage quotient of the $n=1$ step.

The theory of the Josephson effect predicts, and the experimentally observed universality of eq (1) is consistent with the prediction, that K_J is equal to the invariant quotient of fundamental constants $2e/h$, where e is the elementary charge and h is the Planck constant [11]. For the purpose of including data from measurements of fundamental constants in the derivation of their recommended value of K_J, the WGJE assumed that $2e/h=K_J$. However, K_J is not intended to represent the combination of fundamental constants $2e/h$.

2.1.2 Josephson Effect Reference Standard of Voltage The CCE reviewed the report from the WGJE and discussed at some length the draft recommendation E1 (1988), "Representation of the volt by means of the Josephson effect," prepared jointly by the WGJE and the Working Group on the Quantum Hall Effect. The CCE then agreed:

(i) to use the term "Josephson constant" with symbol K_J to denote the Josephson frequency-to-voltage quotient;

(ii) to accept the WGJE's recommended value of K_J, namely, $K_J=(483\ 597.9\pm0.2)$ GHz/V, where the 0.2 GHz/V assigned one-standard-deviation uncertainty corresponds to a relative uncertainty of 0.4 ppm;

(iii) to use this recommended value to define a conventional value of K_J and to denote it by the symbol K_{J-90}, so that $K_{J-90}\overset{\text{def}}{=}483\ 597.9$ GHz/V exactly. (The subscript 90 derives from the fact that this new conventional value of the Josephson constant is to come into effect starting January 1, 1990, a date reaffirmed by the CCE.) The CCE also noted

(iv) that since K_{J-90} exceeds the CCE's 1972 conventional value of the Josephson constant by 3.9 GHz/V or about 8.065 ppm, the new representation of the volt will exceed that based on the 1972 value by about 8.065 ppm; and further agreed

(v) that because the purpose of the new volt representation is to improve the worldwide uniformity of voltage measurements and their consistency with the SI, laboratories which do not base their national representation of the volt on the Joseph-

[5] The complete reports of the Josephson and Quantum Hall Effect Working Groups including the "Technical Guidelines" (Rapports BIPM 88/77, 88/8, and 88/9) will appear in the proceedings of the CCE's 18th meeting [2]. Additionally, a combined, somewhat condensed version of the two reports may be found in reference [3] and the "Technical Guidelines" in reference [10].

son effect should, on January 1, 1990, adjust the value of their national volt representation so that it is consistent with the new representation. Further, this consistency should be maintained by having a transportable voltage standard periodically calibrated by a laboratory that does base its representation of the volt on the Josephson effect;

(vi) that even if future, more accurate measurements of K_J indicate that the recommended value differs from the SI value by some small amount, the conventional value K_{J-90} should not be altered. Rather, the CCE could simply note the difference between a representation of the volt based on K_{J-90} and the volt; and

(vii) that because an accurate representation of the volt is important to science, commerce, and industry, laboratories should continue their efforts to realize the volt with greater accuracy, either directly or indirectly via measurements of fundamental constants. This could lead to a significant reduction in the uncertainty assigned to the new volt representation.

Having concurred on these points, the CCE edited the draft recommendation E1 (1988) to bring it to final form. The following week it was submitted to the CIPM for approval at its 77th meeting held on October 4–6, 1988, at the BIPM. After some minor editorial changes, the CIPM adopted it as its own recommendation [12]. The following is the English language version (the French language version is the official one and is given in references [2] and [12]):

Representation of the Volt by Means of the Josephson Effect

Recommendation 1 (CI-1988)

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

—that a detailed study of the results of the most recent determinations leads to a value of 483 597.9 GHz/V for the Josephson constant, K_J, that is to say, for the quotient of frequency divided by the potential difference corresponding to the $n=1$ step in the Josephson effect,

—that the Josephson effect together with this value of K_J can be used to establish a reference standard of electromotive force having a one-standard-deviation uncertainty with respect to the volt estimated to be 4 parts in 10^7, and a reproducibility which is significantly better,

recommends

—that 483 597.9 GHz/V exactly be adopted as a conventional value, denoted by K_{J-90}, for the Josephson constant, K_J,

—that this new value be used from 1st January 1990, and not before, to replace the values currently in use,

—that this new value be used from this same date by all laboratories which base their measurements of electromotive force on the Josephson effect, and

—that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with the new adopted value,

is of the opinion

—that no change in this recommended value of the Josephson constant will be necessary in the foreseeable future, and

draws the attention of laboratories to the fact that the new value is greater by 3.9 GHz/V, or about 8 parts in 10^6, than the value given in 1972 by the Comité Consultatif d'Électricité in its Declaration E-72.

2.2 Quantum Hall Effect

2.2.1 Definition of the von Klitzing Constant The QHE is characteristic of certain high mobility semiconductor devices of standard Hall-bar geometry when in a large applied magnetic field and cooled to a temperature of about one kelvin. For a fixed current I through a QHE device there are regions in the curve of Hall voltage vs gate voltage, or of Hall voltage vs magnetic field depending upon the device, where the Hall voltage U_H remains constant as the gate voltage or magnetic field is varied. These regions of constant Hall voltage are termed Hall plateaus. Under the proper experimental conditions, the Hall resistance of the ith plateau $R_H(i)$, defined as the quotient of the Hall voltage of the ith plateau to the current I, is given by

$$R_H(i)=U_H(i)/I=R_K/i, \tag{2}$$

where i is an integer [13]. Because $R_H(i)$ is often referred to as the quantized Hall resistance regardless of plateau number, the Working Group on the Quantum Hall Effect (WGQHE) proposed that to avoid confusion, the symbol R_K be used as the Hall voltage-to-current quotient or resistance of the $i=1$ plateau and that it be termed the von Klitzing constant after the discoverer of the QHE. It thus follows from eq (2) that $R_K=R_H(1)$.

The theory of the QHE predicts, and the experimentally observed universality of eq (2) is consistent with the prediction, that R_K is equal to the invariant quotient of fundamental constants h/e^2 [13]. For the purpose of including data from measurements of fundamental constants in the derivation of their recommended value of R_K, the WGQHE assumed that $h/e^2=R_K$. However, in analogy with K_J, R_K is not intended to represent the combination of fundamental constants h/e^2.

2.2.2 Quantum Hall Effect Reference Standard of Resistance The CCE reviewed the report of the WGQHE and discussed the draft recommendation E2 (1988), "Representation of the ohm by means of the quantum Hall effect," prepared jointly by the two Working Groups. Because of the similarities between the QHE and the Josephson effect, the review and discussion proceeded expeditiously. Indeed, the second half of point (iii) as given here in section 2.1.2 on the Josephson effect and all of points (v), (vi), and (vii) were viewed by the CCE as applying to the quantum Hall effect as well. Also in analogy with the Josephson effect, the CCE agreed:

(i) to use the term "von Klitzing constant" with symbol R_K to denote the Hall voltage to current quotient or resistance of the $i=1$ plateau;

(ii) to accept the WGQHE's recommended value of R_K, namely, $R_K=(25\ 812.807\pm0.005)\ \Omega$, where the 0.005 Ω assigned one-standard-deviation uncertainty corresponds to a relative uncertainty of 0.2 ppm; and

(iii) to use this recommended value to define a conventional value of R_K and to denote it by the symbol R_{K-90}, so that $R_{K-90}\overset{\text{def}}{=}25\ 812.807\ \Omega$ exactly.

The same procedure was followed for draft recommendation E2 (1988) as for E1 (1988) regarding the Josephson effect. The final CIPM English language version is as follows:

Representation of the Ohm by Means of the Quantum Hall Effect

Recommendation 2 (CI-1988)

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

—that most existing laboratory reference standards of resistance change significantly with time,

—that a laboratory reference standard of resistance based on the quantum Hall effect would be stable and reproducible,

—that a detailed study of the results of the most recent determinations leads to a value of 25 812.807 Ω for the von Klitzing constant, R_K, that is to say, for the quotient of the Hall potential difference divided by current corresponding to the plateau $i=1$ in the quantum Hall effect,

—that the quantum Hall effect, together with this value of R_K, can be used to establish a reference standard of resistance having a one-standard-deviation uncertainty with respect to the ohm estimated to be 2 parts in 10^7, and a reproducibility which is significantly better,

recommends

—that 25 812.807 Ω exactly be adopted as a conventional value, denoted by R_{K-90}, for the von Klitzing constant, R_K,

—that this value be used from 1st January 1990, and not before, by all laboratories which base their measurements of resistance on the quantum Hall effect,

—that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with R_{K-90},

—that in the use of the quantum Hall effect to establish a laboratory reference standard of resistance, laboratories follow the most recent edition of the "Technical Guidelines for Reliable Measurements of the Quantized Hall Resistance" drawn up by the Comité Consultatif d'Électricité and published by the Bureau International des Poids et Mesures,

and *is of the opinion*

—that no change in this recommended value of the von Klitzing constant will be necessary in the foreseeable future.

2.3 Practical Implementation of Recommendations

As implied by the discussion of section 1, the results of voltage and resistance measurements expressed in terms of representations of the volt and ohm based on the Josephson and quantum Hall effects, respectively, will have a higher precision than the same measurement results expressed in terms of the volt and ohm themselves. Indeed, this is one of the principal reasons for establishing such

representations.[6] The question arises, however, as to how such measurement results should be reported in practice. The Working Groups recognized that the potential for significant confusion internationally could best be eliminated by having each national standards laboratory adopt the same approach. To this end, in their reports the Working Groups identified and considered the advantages and disadvantages of three different approaches to the reporting problem, two of which are both rigorous and correct [2]. In the first, new "practical units" "V_{90}" and "Ω_{90}" are defined; in the second, new, so-called "conventional physical quantities" for electromotive force (and electric potential difference) and resistance, "E_{90}" and "R_{90}," are defined.

The CCE discussed at length the three approaches identified by the Working Groups and concluded that there was an alternative solution, similar to the Working Groups' third approach, that is also rigorous but avoids

(i) defining new practical units of emf and resistance that are likely to differ from the volt and ohm by small amounts and which would be parallel to and thus in competition with the volt and ohm. (Defining such units automatically leads to practical electrical units for current, power, capacitance, etc., thereby giving the appearance that a complete new system of electrical units has been established outside of the SI.) The CCE's alternative solution also avoids

(ii) defining new conventional physical quantities for emf and resistance which are likely to differ from traditional or true emf and resistance by small amounts. (Defining such quantities automatically leads to conventional physical quantities for current, power, capacitance, etc.; and to the peculiar situation of, for example, the same standard cell having both a conventional emf and a true emf.) Further, the alternative solution avoids

(iii) the use of subscripts or other distinguishing symbols of any sort on either unit symbols or quantity symbols. (With the elimination of such subscripts and symbols, for example, those denoting particular laboratories or dates, the national standards laboratories can avoid giving the impression to the users of their calibration services that there is more than one representation of the volt and of the ohm in general use, that there may be significant differences among national realizations of the new volt and ohm representations, and that either the national realizations or the new representations differ significantly from the SI.)

The CCE's solution, which was affirmed by the CIPM at its 77th meeting [12] and which all national standards laboratories are requested to follow, is indicated in the following variation of the example given by the CCE [2] (the treatment of resistance measurements is strictly analogous):

The emf E of an unknown standard cell calibrated in terms of a representation of the volt based on the Josephson effect and the conventional value of the Josephson constant K_{J-90}, may be rigorously expressed in terms of the (SI) volt V as (to be specific):

$$E=(1.018\ 123\ 45)\ \mathrm{V}\pm\epsilon, \tag{3}$$

where ϵ represents the total uncertainty, in volts, and is composed of the following two components: ΔE, the combined uncertainty associated with the calibration itself and with the realization of the Josephson effect volt representation at the particular standards laboratory performing the calibration; and ΔA, the uncertainty with which the ratio K_{J-90}/K_J is known (i.e., it is assumed that $K_{J-90}/K_J=1\pm\Delta A$). According to Recommendation 1 (CI-1988), ΔA is 4 parts in 10^7 or 0.4 ppm (assigned one standard deviation).

Since, by international agreement, ΔA is common to all laboratories, the two uncertainties ΔE and ΔA need not be formally combined to obtain the total uncertainty ϵ but may be separately indicated. Hence, the measured emf E may be expressed as

$$E=(1.018\ 123\ 45)\ \mathrm{V}\pm\Delta E \tag{4}$$

for all practical purposes of precision electrical metrology and trade, with ΔA appearing separately on the calibration certificate when the precision of the calibration warrants it. If, for example, $\Delta E/E$ is significantly greater than 0.4 ppm, ΔA may be omitted with negligible effect.

An example of the wording that might be used on a NIST Report of Calibration for a standard cell enclosure for the case where ΔA may not be omitted and which is a variation of the wording given in an example developed by the CCE [2], is as follows:

[6] As noted by the CCE [2], the Josephson and quantum Hall effects and the values K_{J-90} and R_{K-90} cannot be used to define the volt and ohm. To do so would require a change in the status of the permeability of vacuum μ_0 from an exactly defined constant, thereby abrogating the definition of the ampere. It would also give rise to electrical units which would be incompatible with the definition of the kilogram and units derived from it.

Sample Hypothetical NIST Calibration Report

This standard cell enclosure was received (date) under power at its normal operating temperature.

The values given in the table below are based on the results of daily measurements of the differences between the emfs of the cells in this standard and those of NIST working standards calibrated in terms of the Josephson effect using the new conventional value of the Josephson constant internationally adopted for use starting January 1, 1990 (see Note A). The measurements were made in the period from (date) to (date).

Cell number	emf (volts, V)	Uncertainty (microvolts, μV)
1	1.018 119 85	0.27
2	1.018 133 77	0.27
3	1.018 126 42	0.27
4	1.018 141 53	0.27

(Information relating to the measurements and their uncertainties to be given here.)

Note A

The value of the Josephson constant used in this calibration, namely, K_{J-90}=483 597.9 GHz/V exactly, is that adopted by international agreement for implementation starting on January 1, 1990, by all national standards laboratories that base their national representation of the volt (i.e., their national "practical unit" of voltage) on the Josephson effect. Since all such laboratories now use the same conventional value of the Josephson constant while prior to this date several different values were in use, the significant differences which previously existed among the values of some national representations of the volt no longer exist. Moreover, the national standards laboratories of those countries that do not use the Josephson effect for this purpose are requested to maintain their own national representation of the volt so as to be consistent with the above conventional value of the Josephson constant, for example, through periodic comparisons with a laboratory that does use the Josephson effect. An ideal representation of the volt based on the Josephson effect and K_{J-90} is expected to be consistent with the volt as defined in the International System of Units (SI) to within an assigned relative one-standard-deviation uncertainty of 0.4 ppm (0.41 μV for an emf of 1.018 V). Because this uncertainty is the same for all national standards laboratories, it has not been formally included in the uncertainties given in the table. However, its existence must be taken into account when the utmost consistency between electrical and nonelectrical measurements of the same physical quantity is required.

2.4 Future Work on Electrical Units

The ideas agreed upon by the CCE as given in point (vii) in Sect. 2.1.2 on the Josephson effect, and which apply equally as well to the quantum Hall effect, led the CCE to adopt the following formal recommendation which was also approved by the CIPM at its 77th meeting [12].

Realization of the Electrical SI Units

Recommendation E3 (1988)

The Comité Consultatif d'Électricité
recognizing
—the importance to science, commerce and industry of accuracy in electrical measurements,
—the fact that this accuracy depends on the accuracy of the reference standards of the electrical units,
—the very close ties that now exist between electrical metrology and fundamental physical constants,
—the possibility of obtaining more accurate reference standards of the electrical units either directly from the realizations of their definitions or indirectly from measurements of fundamental constants, and
—the continuing need to compare among themselves independent realizations of the units and independent measurements of fundamental constants to verify their accuracy,
recommends
—that laboratories continue their work on the electrical units by undertaking direct realizations of these units and measurements of the fundamental constants, and
—that laboratories pursue the improvement of the means for the international comparison of national standards of electromotive force and electrical resistance.

3. Conclusion

The apparatus currently being used by the national standards laboratories is such that the total experimental uncertainty associated with a particular national representation of the volt based on the Josephson effect generally lies in the range 0.01 to 0.2 ppm. As a consequence, with the worldwide adoption starting January 1, 1990, of the new conventional value of the Josephson constant K_{J-90}, all national representations of the volt should be equivalent to within a few tenths of a ppm. Similarly, the total experimental uncertainty associated with the measurement of quantized Hall resistances also generally lies in the range 0.01 to 0.2 ppm. Hence, with the worldwide adoption starting on January 1, 1990, of a new representation of the ohm based on the QHE and the conventional value of the von Klitzing constant R_{K-90}, all national representations of the ohm should also be equivalent to within a few tenths of a ppm. Moreover, these new national volt and ohm representations should be consistent with the volt and the ohm to better than 0.5 ppm.

In the U.S., the value of the present national representation of the volt maintained by NIST will need to be increased on January 1, 1990, by about 9.26 ppm to bring it into agreement with the new representation of the volt. This is sufficiently large that literally thousands of electrical standards, measuring instruments, and electronic systems throughout the Nation will have to be adjusted or recalibrated in order to conform with the new representation. Most other countries will be required to make a similar change in the value of their present representation of the volt as can be seen from figure 1. On the same date, the value of the U.S. representation of the ohm maintained by NIST will need to be increased by about 1.69 ppm to bring it into agreement with the new representation of the ohm based on the quantum Hall effect. This too is an amount which is of significance to many existing standards, instruments, and systems.

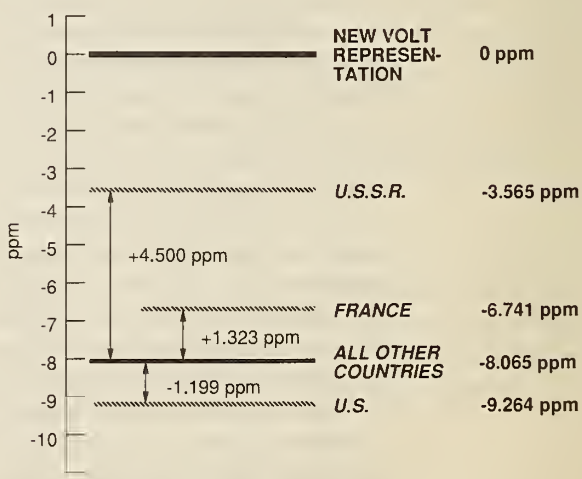

Figure 1. Graphical comparison of the value of the present representation of the volt of various countries as based on the Josephson effect, with the new representation of the volt based on the Josephson effect and the CIPM conventional value of the Josephson constant K_{J-90} which is to come into effect starting on January 1, 1990. The value of the volt representation indicated by "All Other Countries" is based on the conventional value of the Josephson constant stated by the CCE in 1972, namely, 483 594 GHz/V. The countries that currently use this value include Australia, Canada, Finland, F.R.G., G.D.R., Italy, Japan, The Netherlands, and the U.K. The BIPM uses this value as well, but NIST uses 483 593.420 GHz/V. Thus, as the figure shows, on January 1, 1990, the value of the present U.S. volt representation will need to be increased by 9.264 ppm to bring it into conformity with the new representation.

The change required in the value of the national representation of the ohm of other countries varies between a decrease of a few tenths of a ppm to an increase in excess of 3 ppm.

Since $A = V/\Omega$ where A is the ampere as defined in the SI; and $W = V^2/\Omega$ where W is the watt as defined in the SI, the 9.264 ppm and 1.69 ppm increase in the U.S. representation of the volt and of the ohm, respectively, imply that on January 1, 1990, (i) the U.S. representation of the ampere will increase by about 7.57 ppm and (ii) the U.S. electrical representation of the watt will increase by about 16.84 ppm. Because an ideal volt representation based on the Josephson effect and K_{J-90} is expected to be consistent with the volt to within an assigned relative one-standard-deviation uncertainty of 0.4 ppm; and an ideal ohm representation based on the QHE and R_{K-90} is expected to be consistent with the ohm to within an assigned one-standard-deviation uncertainty of 0.2 ppm, ampere and watt representations derived from such ideal volt and ohm representations via the above equations are expected to be consistent with the ampere and watt to within a one-standard-deviation uncertainty of 0.45 ppm and 0.83 ppm, respectively.

The CCE strongly believes, and the author fully concurs, that the significant improvement in the international uniformity of electrical measurements and their consistency with the SI which will result from implementing the new representations of the volt and ohm will be of major benefit to science, commerce, and industry throughout the world; and that the costs associated with implementing the new representations will be far outweighed by these benefits.

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News from the BIPM

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Comité International des Poids et Mesures

77th Meeting

The Comité International des Poids et Mesures (CIPM) at its 77th Meeting, held at the Pavillon de Breteuil on the 4th, 5th and 6th of October 1988, adopted two important Recommendations concerning the use of the Josephson effect and the quantum Hall effect for maintaining reference standards for the measurement of emf and resistance. These Recommendations are based upon proposals made to the CIPM by its Comité Consultatif d'Electricité (CCE) which met in September 1988. The CCE proposals were the result of a great deal of work and discussion that had taken place among representatives of the national standards laboratories and the BIPM, particularly over the past twelve months.

New determinations of the SI volt and ohm, directly by realizations of the SI definitions and indirectly through determinations of the relevant fundamental physical constants, have established the values of the Josephson constant K_J and the von Klitzing constant R_K of the quantum Hall effect with uncertainties of a few parts in 10^7. The constants K_J and R_K were assumed by the CCE to be equal to $2\,e/h$ and h/e^2 respectively for the purpose of including determinations of fundamental constants in their evaluation. The reproducibility, however, of the emf across a Josephson junction and the resistance of a quantum Hall device is much better than a few parts in 10^7 and approaches one part in 10^8. Furthermore, the value of $2\,e/h$ suggested by the CCE in 1972 is now known to be in error by about 8 parts in 10^6, although not all national standards laboratories are using this value.

In order to unify world reference standards of emf and allow users to take advantage of the great reproducibility of the Josephson effect and the quantum Hall effect, the CIPM acted on the advice of the CCE and adopted particular values of K_J and R_K, designated K_{J-90} and R_{K-90}, for use by all laboratories beginning on 1st January 1990. For those countries that have based their reference standard of emf on the Josephson junction and use the 1972 CCE value for $2\,e/h$, the adoption of the new value for K_J will lead to a change in their reference standards of about 8 parts in 10^6, i.e. 8 μV per volt. For the countries using values of K_J which differ from the 1972 CCE value, the changes will be within the range of about 9 to 3.5 parts in 10^6.

Also 1st January 1990 it is expected that a new international temperature scale, the International Temperature Scale of 1990 (ITS-90), will come into effect, which will replace the International Practical Temperature Scale of 1968 (IPTS-68). The differences between ITS-90 and IPTS-68 are significant; not only are the scales substantially different in definition but temperatures measured on the ITS-90 differ significantly from those measured on the IPTS-68. For example, near room temperature: for $t_{68} \simeq 20\,°C$ the difference $T_{90} - T_{68} \simeq -5$ mK and for $t_{68} \simeq 100\,°C$ the difference $T_{90} - T_{68} \simeq -25$ mK. The normal boiling point of water thus will be about 99.97 °C and not 100.00 °C as in the past.

It is important that users be made aware of these changes in electrical and temperature reference standards well in advance of their introduction. For this reason the 18th Conférence Générale des Poids et Measures asked the CIPM to announce one year in advance, namely at the beginning of 1989, the magnitude of the changes consequent upon their coming into effect.

These official announcements are now made in the following three CIPM recommendations:

Representation of the volt by means of the Josephson effect

Recommendation 1 (CI-1988)

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et

Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

– that a detailed study of the results of the most recent determinations leads to a value of 483 597.9 GHz/V for the Josephson constant, K_J, that is to say, for the quotient of frequency divided by the potential difference corresponding to the $n = 1$ step in the Josephson effect,

– that the Josephson effect together with this value of K_J can be used to establish a reference standard of electromotive force having a one-standard-deviation uncertainty with respect to the volt estimated to be 4 parts in 10^7, and a reproducibility which is significantly better,

recommends

– that 483 597.9 GHz/V exactly be adopted as a conventional value, denoted by K_{J-90}, for the Josephson constant, K_J,

– that this new value be used from 1st January 1990, and not before, to replace the values currently in use,

– that this new value be used from this same date by all laboratories which base their measurements of electromotive force on the Josephson effect, and

– that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with the new adopted value,

is of the opinion

– that no change in this recommended value of the Josephson constant will be necessary in the foreseeable future, and

draws the attention of laboratories to the fact that the new value is greater by 3.9 GHz/V, or about 8 parts in 10^6, than the value given in 1972 by the Comité Consultatif d'Electricité in its Declaration E-72.

Representation of the ohm by means of the quantum Hall effect

Recommendation 2 (CI-1988)

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

– that most existing laboratory reference standards of resistance change significantly with time,

– that a laboratory reference standard of resistance based on the quantum Hall effect would be stable and reproducible,

– that a detailed study of the results of the most recent determinations leads to a value of 25 812.807 Ω for the von Klitzing constant, R_K, that is to say, for the quotient of the Hall potential difference divided by current corresponding to the plateau $i = 1$ in the quantum Hall effect,

– that the quantum Hall effect, together with this value of R_K, can be used to establish a reference standard of resistance having a one-standard-deviation uncertainty with respect to the ohm estimated to be 2 parts in 10^7, and a reproducibility which is significantly better,

recommends

– that 25 812.807 Ω exactly be adopted as a conventional value, denoted by R_{K-90}, for the von Klitzing constant, R_K,

– that this value be used from 1st January 1990, and not before, by all laboratories which base their measurements of resistance on the quantum Hall effect,

– that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with R_{K-90},

– that in the use of the quantum Hall effect to establish a laboratory reference standard of resistance, laboratories follow the most recent edition of the technical guidelines for reliable measurements of the quantized Hall resistance drawn up by the Comité Consultatif d'Electricité and published by the Bureau International des Poids et Mesures, and

is of the opinion

– that no change in this recommended value of the von Klitzing constant will be necessary in the foreseeable future.

Preparation of the International Temperature Scale of 1990 (ITS-90)

Recommendation 3 (CI-1988)

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 7 of the 18th Conférence Générale des Poids et Mesures concerning the preparation of the new international temperature scale,

announces that the differences between the ITS-90 and the IPTS-68 will be approximately those indicated in the graph attached to this Recommendation,

recommends that national laboratories take note of these differences with a view to the implementation of the ITS-90 on 1st January 1990.

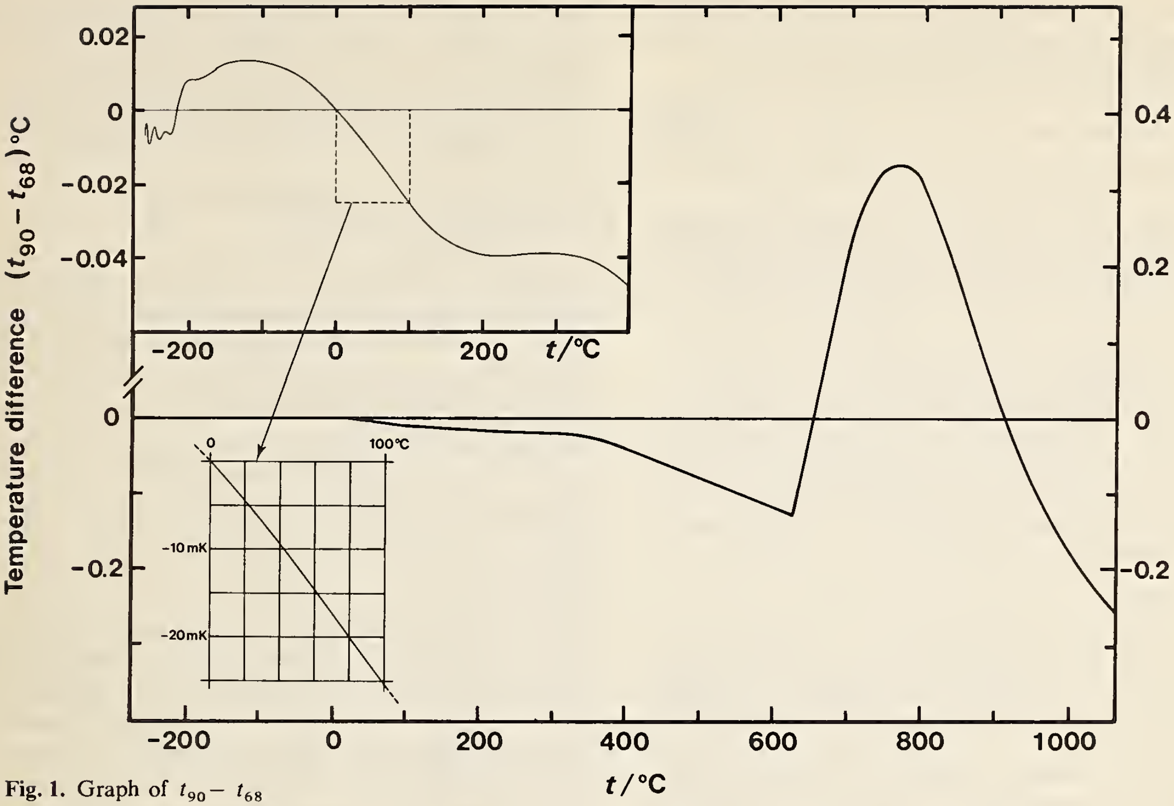

Fig. 1. Graph of $t_{90} - t_{68}$

Comité Consultatif d'Electricité

18th Meeting

The CCE at its meeting in September 1988 considered very carefully the way in which the recommended values for K_J and R_K (defined above) be used. Although no formal recommendation was made on this point, the following four statements were drafted and unanimously approved by the CCE and subsequently supported by the CIPM [1]:

1.1. Recommendations 1 (CI-1988) and 2 (CI-1988) do not constitute a redefinition of SI units

The conventional values K_{J-90} and R_{K-90} cannot be used as bases for defining the volt and ohm (meaning the present volt and ohm units in the Système International d'Unités). To do so would change the status of μ_0 from that of a constant having an exactly defined value (and would therefore abrogate the definition of the ampere) and would also produce electrical units which would be incompatible with the definition of the kilogram and units derived from it.

[1] Because the original draft CCE recommendations were slighly modified by the CIPM, I have chosen to refer here only to the CIPM designations, i.e., CI-1988.

1.2. Concerning the use of subscripts on symbols for quantities or units

The CCE considers that symbols for electromotive force (electric potential, electric potential difference) and electric resistance, and for the volt and the ohm, should not be modified by adding suffixes to denote particular laboratories or dates.

The principal reasons for this viewpoint with respect to the physical quantities are that:

– until now, temperature being one of the very few exceptions, it has not been necessary to introduce explicitly the concept of a system of conventional physical quantities differing from the traditional quantities,

– it would be difficult to make such a concept widely understood and accepted,

– the concept, if introduced for electromotive force and electrical resistance, would propagate to other quantities.

The principal reasons for this viewpoint with respect to the units are that:

– the appearance of creating a unit system other than SI should be avoided, particularly as this would propagate to units for other quantities,

– the new reference standards will be completely satisfactory representations of the volt and the ohm for the great majority of applications,

– any disagreement between those laboratories that realize the new reference standards will be negligible from the point of view of the great majority of users,

– many countries are in any case constrained by their existing legislation concerning physical quantities and units to use the SI names and symbols.

1.3. Concerning the practical implementation of the Recommendations 1 (CI-1988) and 2 (CI-1988)

The CCE having carefully considered the three approaches listed in the reports of the Working Groups, documents CCE/88-34 and CCE/88-35 [2], is of the opinion that a rigorous solution to this problem has been identified which avoids

(i) defining new units "V_{90}" or "Ω_{90}",
(ii) defining new physical quantities "E_{90}" or "R_{90}",
(iii) the use of subscripts or other distinguishing symbols of any sort on either unit symbols or quantity symbols.

The preferred approach is indicated in the following example of a statement that may be communicated to users of standard-cell calibration certificates:

The measured emf, E, or electric potential difference, U, of the unknown source may be rigorously expressed in terms of the SI volt, V, as:

$$E = (1.018 \text{ xxx xx}) \text{ V} \pm \varepsilon$$

The symbol ε represents the total uncertainty, at the level of one standard deviation, and is given by

$$\varepsilon = [(\Delta E)^2 + (E \cdot \delta)^2]^{1/2}$$

where ΔE is the combined uncertainty in volts (at one standard deviation) associated with the calibration itself and with the realization of the Josephson-effect reference standard at the particular national standards laboratory, and δ represents the relative uncertainty with which the ratio K_{J-90}/K_J is known. At present δ is estimated to be 4×10^{-7} (one standard deviation) according to Recommendation 1 (CI-1988).

Since, by international agreement, δ is common to all laboratories, it may be indicated separately and the above expression for E may be rewritten

$$E = (1.018 \text{ xxx xx}) \text{ V} \pm \Delta E$$

for all practical purposes of precision electrical metrology and trade. However, when this is done, δ should appear separately on the certificate where the precision is such as to require it. When $\Delta E/E$ is significantly greater than 4×10^{-7}, δ may be omitted.

The treatment of resistance measurements [Recommendation 2 (CI-1988)] is strictly analogous.

[2] Note to reader: these two Documents dealt with the Josephson effect and the quantum Hall effect, respectively.

1.4. Example of the wording to be used on calibration certificates

The values of emf below are based on ... [a description of the calibration procedure may be placed here] ... using the new conventional value of the Josephson constant internationally adopted for use from 1st January 1990 (see Note A).

cell number	emf in volts	uncertainty in volts
1	1.018 123 4	ΔE

[other data related to the calibration may be placed here]

Note A
The value of the Josephson constant used in this calibration is $K_{J-90} = 483\,597.9$ GHz/V and is that adopted, by international agreement, for implementation on 1st January 1990 by all national standards laboratories that use the Josephson effect as a reference standard of the volt. By international agreement, all such laboratories now use the same value of the Josephson constant whereas until recently they did not. National standards laboratories of those countries that do not use the Josephson effect as a reference standard can maintain their own reference standards so as to be consistent with the above value of the Josephson constant, by periodic comparisons with a laboratory that does use the Josephson effect. An ideal reference standard of emf based on the Josephson effect and K_{J-90} is consistent with the SI volt within an assigned fractional one-standard-deviation uncertainty of 4×10^{-7} (0.4 μV for an emf of one volt). Because this uncertainty is the same for all national standards laboratories, it has not been formally included in the uncertainties given in the table. However, its existence must be recognized when the utmost consistency between electrical and mechanical measurement is required.

Comité Consultatif pour la Masse et les grandeurs apparentées

3rd Meeting

The Comité Consultatif pour la Masse et les grandeurs apparentées (CCM) met at the Pavillon de Breteuil on the 26th and 27th of May 1988. The President, Prof. Bray, being indisposed the meeting was chaired by Dr. Giacomo, Director of the BIPM. The CCM covers a wide range of activities in the fields of mass,

force and pressure standards and much of the meeting was devoted to the examination of reports drawn up by the nine Working Groups. Most of these Working Groups had met in the days immediately preceding the meeting of the CCM. The fields of work covered by the Working Groups were: 1, the measurement of air density; 2, the conservation and behaviour of Pt/Ir mass standards; 3, the conservation and behaviour of stainless-steel mass standards; 4, the measurement of the density of liquids and solids; 5, force measurement; 6, 7, 8 and 9, the measurement of high, medium, low and very low pressures, respectively.

In many of these fields, in addition to the individual and collaborative projects under way, international comparisons had taken place or were in progress and reports were presented. The CCM also discussed recent advances in high-accuracy weighing and balance design and the third verification of national prototypes of the kilogram now in its preliminary stages at the BIPM. It is expected that the first part of this operation, the comparison of the international prototype with its copies at the BIPM, will have been completed by the end of 1988. Over the next three years or so, national prototypes will come to the BIPM in groups for verification. Since the last time such a large scale verification took place, some forty years ago, the accuracy of the best balances has improved by at least a factor of ten. The present verification is being carried out using the NBS-2 balance which is a single-pan, knife-edge balance that has an accuracy of about 1 μg in the comparison of Pt/Ir mass standards, i. e. a relative uncertainty at the level of one standard deviation of about 1 part in 10^9.

Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants

Section I (X-rays, γ-rays and electrons) and Section III (Neutrons) of the Comité Consultatif pour les Etalons de Mesure de Rayonnements Ionisants (CCEMRI) met from 8th to 11th and 18th to 20th of April respectively. During the meeting of Section I, the work of the BIPM was reviewed and the results of recent comparisons of national standards were discussed. The need for comparisons of absorbed-dose standards for radiation of energy above 1 MeV was stressed. Two Recommendations were adopted and sent to the CCEMRI for approval at its next meeting. At the meeting of Section III, the BIPM work on neutron measurements was reviewed. The published results of completed neutron-emission-rate and fluence-rate comparisons, the NPL neutron-dosimetry comparison and the preliminary report on the BIPM neutron-dosimetry comparison were all discussed.

Work in the BIPM Laboratories

Among the principal activities in the laboratories of the BIPM over the past year have been the following:

– Electricity section: a limited comparison of 1 Ω national reference standards of resistance was carried out to check the consistency among the various realizations of the quantum Hall effect now being made in 11 national laboratories and the BIPM. Expressed in terms of the BIPM's representation of the ohm, $\Omega_{69-\mathrm{BI}}$, on the central date of the comparison, the measured results for the quantized Hall resistance in five of the six laboratories claiming uncertainties of 4 parts in 10^8 or less are within a range of 7 parts in 10^8. The overall spread of all results was 6 parts in 10^7. Refinements in the BIPM quantum-Hall-effect system, based upon a cryogenic current comparator, now allow $\Omega_{69-\mathrm{BI}}$ to be monitored with an uncertainty of 1.5 parts in 10^8.

Using Josephson junctions made from the new high-T_c superconducting material a measurement of $2e/h$ was made having an uncertainty of 3 parts in 10^6 and which differed from the value obtained from a metallic Josephson junction by about 5 parts in 10^6.

– Mass section: as already mentioned, work began on the third international verification of national prototypes of the kilogram. The BIPM flexure-strip balance has been used to carry out an experiment to search for a nuclear-isospin-coupled "fifth-force". No evidence for the existence of such a force was found, but during the experiment weighings of 2.3 kg masses were carried out that showed remarkably small standard deviations of about 5 parts in 10^{12}.

– Time section: as part of the regular analysis of clock comparisons made using the GPS satellites which go to make up International Atomic Time (TAI) and Universal Coordinated Time (UTC), it was found that for laboratories within about 1000 km of each other errors in coordinates could be discerned and corrected for with an accuracy of about 15 cm in the geocentric coordinates x, y and z. As a result, time comparisons between these (European) laboratories can now be made to within a few nanoseconds.

– Laser section: important international comparisons of laser wavelengths and frequencies have been carried out between a total of 8 countries, mostly at wavelengths in the visible ($\lambda = 633$ mm) but also one in the infrared ($\lambda = 3.39$ μm). Uncertainties in these comparisons are at level of about 1 part in 10^{11} and differences between lasers from participating countries were found, in many cases, to be hardly greater than this.

– Ionizing radiations section: participation in the international comparison of the measurements of activity of iodine-125 has begun. Two methods of spectrum analysis are being used in order to understand better the results obtained earlier during a limited comparison of measurement of activity of the same nuclide. The long-term work on counting methods and counting statistics continues with much emphasis now being placed on the method of 'generalized dead times'.

– Radiometry: new work has begun in radiometry. Equipment has been built and is now in operation for the comparison of calibrations of silicon diodes and thermopiles. The method of self-calibration of silicon diodes has been used and experience is being gained so that international comparisons and, in due course, calibrations can be carried out at the BIPM.

Other News

During the meeting of the CIPM in October 1988 a new building (of some 900 m^2 in surface) was inaugurated. It will house a library and offices for scientific staff, the secretariat and the Director. This completes the second stage of a long-term plan for buildings at the BIPM, the first stage of which was a new laboratory building for laser work opened in 1984.

On 31st July 1988 Dr. P. Giacomo, who had been Director of the BIPM since 1978, retired and was succeeded by Dr. T. J. Quinn, previously Deputy Director.

Publications

Since October 1987 the BIPM has published:

18^e Conférence Générale des Poids et Mesures (1987), Comptes Rendus, 108 pages.

Procès-verbaux des séances du Comité International des Poids et Mesures, tome 55 (76^e session, octobre 1987), 178 pages.

Comité Consultatif de Photométrie et Radiométrie, 11^e session (1986), 183 pages.

Comité Consultatif de Thermométrie, 16^e session (1987), 162 pages.

Rapport Annuel du BIH pour 1987 (about 72 pages covering the contribution of the BIPM on time scales).

Circulaire D du BIH (monthly) (contribution of the BIPM on time scales).

Circulaire T (monthly), circular of the BIPM taking over the part "Temps" of the circular D of the BIH (Circular T1 for January 1988 was published on March 1st, 1988).

Le BIPM et la Convention du Mètre, illustrated brochure in French and in English, 47 pages, widely circulated through various national laboratories.

One should also mention some 40 articles published by staff members in scientific journals and a dozen BIPM reports; the complete list of these publications may be found in the Procès-Verbaux du CIPM, 77th meeting (1988), which will appear in 1989.

Copies of these documents may be obtained upon application to: Mr le Directeur du BIPM, Pavillon de Breteuil, F-92312 Sèvres Cedex, or from the Librairie Offilib, 48 rue Gay-Lussac, F-75240 Paris Cedex 05.

Special Report on Electrical Standards

Report on the 17th Session Of the Consultative Committee On Electricity

Volume 92 Number 1 January–February 1987

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This report provides the background for and summarizes the main results of the 17th session of the Consultative Committee on Electricity (CCE) of the International Committee of Weights and Measures held in September 1986. Included are decisions made by the CCE which promise to have a profound effect on the standardization of national representations of the volt and ohm and thus on the international compatibility of electrical measurements. In particular, on January 1, 1990, worldwide changes in the basis for such representations are planned which will lead to an increase in the U.S. legal unit of voltage of about 9 parts-per-million (ppm) and in the U.S. legal unit of resistance of about 1.5 ppm.

Key words: Consultative Committee on Electricity; electrical units; Josephson effect; ohm; quantum Hall effect; volt.

Accepted: December 11, 1986

1. Background

The 17th session of the Consultative Committee on Electricity (CCE) of the International Committee of Weights and Measures (CIPM) met September 16–18, 1986, at the International Bureau of Weights and Measures (BIPM), which is located in Sèvres (a suburb of Paris), France. NBS Director Ernest Ambler, who was recently elected President of the CCE by the CIPM, chaired the meeting and the author attended as NBS representative.

The CCE is one of eight CIPM Consultative Committees which together cover most of the areas of basic metrology [1][1] (see fig. 1). These committees, which may form temporary or permanent 'Working Groups' to study special subjects, coordinate the international work carried out in their respective fields, assist the CIPM in supervising the work of the BIPM in these fields, and propose recommendations concerning amendments to be made to the definitions and values of units. The CIPM acts directly on these recommendations or submits them for approval to the General Conference of Weights and Measures (CGPM) if they will have a broad impact.

The BIPM, whose principal task is to ensure worldwide uniformity of physical measurements, was established by the Treaty of the Meter signed in Paris on May 20, 1875. (The number of signatories, originally 17, has now grown to almost 50.) The BIPM is supervised by the CIPM which in turn is under the authority of the CGPM. The CGPM consists of delegates from all of the member countries of the Treaty of the Meter and presently meets every four years. The CIPM consists of 18 members each representing a different country and presently meets every year. In general, a consultative committee meets every few years, has as its president a member of the CIPM, and is composed of delegates from the major national standards

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[1]Numbers in brackets indicate literature references.

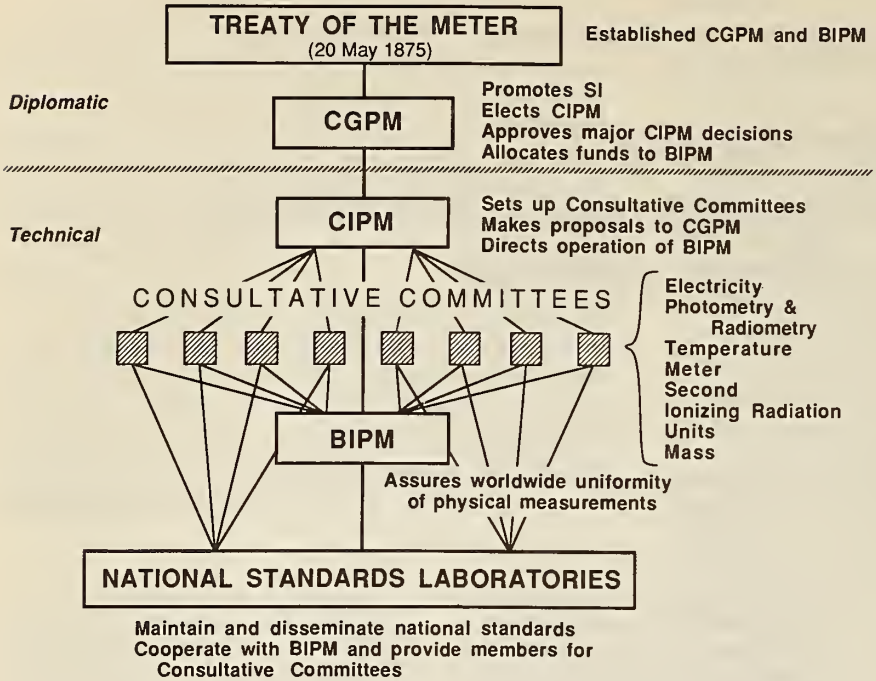

Figure 1–Schematic depiction of how basic measurement units and standards are coordinated internationally. (Treaty of the Meter: *La Convention du Mètre*; CGPM: *Conférence Général des Poids et Mesures* or General Conference of Weights and Measures; CIPM: *Comité International des Poids et Mesures* or International Committee of Weights and Measures; BIPM: *Bureau International des Poids et Mesures* or International Bureau of Weights and Measures.)

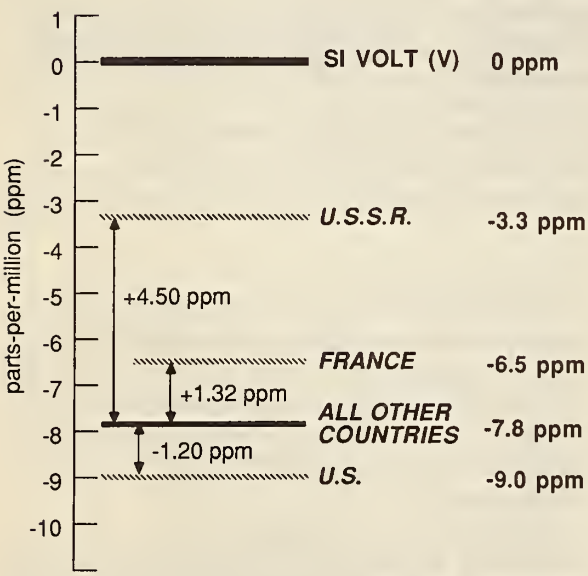

Figure 2–Graphical comparison of the representation of the SI volt of various countries based on the Josephson effect, V_{LAB}, and of V_{LAB} with the SI volt, V. The value of V_{LAB} indicated by 'All Other Countries' is based on the value of the Josephson frequency-voltage ratio $2e/h$ recommended by the CCE of the CIPM in 1972: $(2e/h)_{CCE-72} = 483594.0$ GHz/V. (See footnote 2 for those countries which use this value.)

laboratories as well as from specialized institutes, and individual members appointed by the CIPM.

The focus of the 17th session of the CCE, which was attended by some 30 individuals from 15 countries, was the use of the Josephson and quantum Hall effects to define and maintain national or laboratory representations of the units of electrical potential difference and resistance of *Le Système International d'Unités* or International System of Units (abbreviated SI): the SI volt (V) and SI ohm (Ω), respectively [2]. (The national representations are usually designated by the symbol V_{LAB} and Ω_{LAB} where LAB stands for the acronym of the national standards laboratory of the country in question, e.g., NBS.) More specifically, at its 16th session in March 1983 the CCE had concluded that [3] (see fig. 2):

(i) The value 483594.0 GHz/V for the Josephson frequency-voltage ratio $2e/h$ (e is the elementary charge and h is the Planck constant) which it had recommended at its 13th session in 1972 [4–7] for defining and maintaining national representations of the SI volt is significantly in error. (Current evidence indicates that $(2e/h)_{CCE-72}$ is about eight parts-per-million or 8 ppm smaller than the SI value of $2e/h$ and thus V_{LAB} is about 8 ppm smaller than V for those national laboratories which use the CCE value [2,8].)

(ii) It was highly likely that the recently discovered quantum Hall effect would soon be developed to the point that the quantized Hall resistance $R_H = h/e^2 = 25812.8\ \Omega$ could be used to define and maintain national units of resistance consistent with the SI ohm to

within a few tenths of a ppm. (More recent work indicates that a few hundredths of a ppm is quite feasible [9].)

The CCE was also aware of the following:

(iii) Four different values of $2e/h$ are in use in the national laboratories [2]. [The U.S., France, and the U.S.S.R. use values of $2e/h$ which differ by -1.20 ppm, $+1.32$ ppm, and $+4.50$ ppm, respectively from $(2e/h)_{\text{CCE-72}}$ and hence the national voltage units of these countries differ by these amounts from the national units of those countries which use $(2e/h)_{\text{CCE-72}}$.[2]]

(iv) The various national units of resistance, most of which are based on the mean resistance of a group of precision wire-wound resistors, differ from each other and the SI unit by up to several ppm and some are drifting in excess of 0.05 ppm per year. (Current evidence indicates that on January 1, 1986, the various Ω_{LAB} were from 0.2 ppm larger to 3.3 ppm smaller than Ω and $d\Omega_{\text{LAB}}/dt$ lies in the range -0.07 to $+0.07$ ppm/year [8].)

As a consequence of (i) through (iv), the CCE decided at its 16th session in 1983 to hold its 17th session in 1986 in order to consider the possibility of recommending for adoption a new value for $2e/h$, consistent with the SI, to be used by every laboratory which employs the Josephson effect to define and maintain its representation of the SI volt; and a value of R_{H}, consistent with the SI, to be used by every laboratory which chooses to employ the quantum Hall effect to define and maintain its representation of the SI ohm.[3]

Considerable preparatory work was carried out during the two years prior to the CCE's 17th session:

- Immediately after the formal close of the 1984 Conference on Precision Electromagnetic Measurements (CPEM 84, held August 20–24, 1984, in Delft, The Netherlands), active research workers from the national standards laboratories and other interested parties met informally to discuss values of $2e/h$ and R_{H}. Many new and relevant results were also presented at the conference itself [10].
- In the U.S., NBS Director Ambler sent a letter in early 1985 to over 30 U.S. organizations, companies, and individuals representing industry, government, science, and academia and having an interest in basic electrical measurements and standards at the highest levels of accuracy. The purpose of the letter was to give the U.S. scientific and technological communities the opportunity, well in advance of the 1986 CCE meeting, to provide NBS with advice and guidance on the subject of changing the U.S. electrical units. (The U.S. Legal Volt V_{NBS} would increase by about 9 ppm and the U.S. Legal Ohm Ω_{NBS} by about 1.5 ppm if the CCE were to recommend a new value for $2e/h$ consistent with the SI and a value of R_{H} also consistent with the SI.) The comments received were presented during CPEM 86 (held at NBS Gaithersburg, June 23–27, 1986) at a special session with active audience participation entitled "Changes in the Electrical Units." In addition to the U.S. presenter, viewpoints from other countries were given by speakers from the Federal Republic of Germany, Japan, and the U.K.[4] The three key points which emerged from this session were:

  (a) Changing national voltage and resistance units will outweigh the considerable costs of making the changes if and only if complete international uniformity of all the national units of the industrialized countries is achieved.

  (b) The changes must be well justified by the data; all of the available information must be analyzed by knowledgeable experts and no changes made unless the uncertainties in the values of $2e/h$ and R_{H} are sufficiently small that it is highly unlikely that further changes will be necessary in the forseeable future.

  (c) At least one year should be allowed from the date of the official announcement that the changes will take place to the date of their actual implementation so that industry will have sufficient time to prepare itself properly.

- Many researchers took the occasion of CPEM 86 to present their latest results on values of $2e/h$ and R_{H} [11].
- There was an informal meeting of active research workers and other interested parties to discuss values of $2e/h$ and R_{H} just after the close of CPEM 86 as there was at the close of CPEM 84.

[2] These include Australia, Canada, the Federal Republic of Germany, Finland, the German Democratic Republic, Italy, Japan, The Netherlands, and the U.K., as well as the BIPM.

[3] Basing Ω_{LAB} on R_{H} would, of course, eliminate the drift in Ω_{LAB} (i.e., make $d\Omega_{\text{LAB}}/dt=0$).

[4] Written versions of the talks given during the session will appear in Ref. [11].

- Fifty-nine documents were submitted to the CCE by the CCE members (i.e., by the national standards laboratories of the member countries) in support of the CCE's deliberations. These documents included new results as well as comments on the key issues facing the CCE concerning the adoption of a new value for $2e/h$ and a value of R_H.
- A detailed provisionary agenda containing some 25 items was prepared for the 1986 CCE meeting with extensive supporting material in succinct, summary form [12].

2. CCE 17th Session Discussions and Principal Decisions

2.1 Josephson Effect

The principal Josephson effect topics reviewed in detail by the CCE were [12] (i) the value of $2e/h$ used by each national standards laboratory to maintain its representation of the SI volt and the accuracy achieved; (ii) the observed agreement among national voltage standards based on the Josephson effect; (iii) the uncertainties associated with intercomparing these voltage standards using transportable standard cells and Zener diode devices; (iv) the values of $2e/h$ in SI units and their uncertainties obtained by direct force balance measurements and indirectly from fundamental constant determinations; (v) the prospects for future SI values of $2e/h$ with their expected uncertainties and dates of availability; and (vi) the need for further intercomparisons of national voltage standards and Josephson apparatus.

With regard to (i), the uncertainties achieved were noted to be generally in the range 0.01 to 0.1 ppm[5], although Josephson arrays may enable uncertainties smaller than 0.01 ppm to be achieved routinely [13]. Under (ii) and (iii), it was concluded that the agreement between national Josephson voltage standards was generally better than 0.1 ppm but that it was difficult to demonstrate this level of consistency using volt transfer standards. With regard to (iv) and (v), the CCE decided that although the data currently available (both direct and indirect) could provide a value of $2e/h$ in SI units with an uncertainty of about 0.2 ppm, additional data expected to be available within two years would significantly increase confidence in the reliability of the value. Finally, under (vi), the CCE concluded that a formal, broadly based, international comparison of national units of voltage would not be useful because of the unreliability of volt transfer standards but that those laboratories involved in determinations of $2e/h$ should attempt to compare their units using the best transfer standards at their disposal.

[5] Throughout this paper, all uncertainties are one standard deviation estimates.

The result of the CCE's review of these Josephson effect topics was the following formal declaration:

Declaration E 1 (1986)

Concerning the Josephson effect for maintaining the representation of the volt.

The Comité Consultatif d'Electricité

recognizes

– that as an organ of the Convention du Mètre one of its responsibilities is to ensure the propagation and improvement of the SI, the unit system in use throughout the world,

– that worldwide uniformity and constancy over a long period of time of national representations of the volt are of great technical and economic importance to commerce and industry,

– that many national standards laboratories use the Josephson effect to maintain a highly stable representation of the volt but that not all use the same value for the quotient frequency to voltage,

– that the value of this quotient (483594.0 GHz/V) declared by the CCE in 1972 and which most national laboratories use to maintain representations of the volt is now known to be in error by a significant amount,

– that various laboratories have carried out direct realizations of the volt or determinations of fundamental constants which can yield an indirect value of $2e/h$ in SI units,

– that other national laboratories expect shortly to complete similar realizations or determinations,

is of the opinion

– that the value of the quotient frequency to voltage used to maintain a realization of the volt by means of the Josephson effect must be consistent with the SI,

– that a new value, more consistent with SI, can soon be adopted for use by all laboratories,

– that this new value should be adopted simultaneously by all countries concerned,

in consequence, the CCE

– **establishes** a Working Group charged with making a proposal to the CCE for a new value to be based upon all relevant data that become available before June 15, 1988,

– **decides** to meet in September 1988 with a view to recommending the new value of this quotient to come into effect on January 1, 1990,

– **gives notice** that the new value is likely to be higher than the present one by about 8 parts in 10^6, furthermore, the CCE

– **recommends** that national laboratories vigorously pursue their work on the realizations of the volt, the intercomparison of these realizations, and the determination of the constants in question and communicate without delay all their results to the Working Group,

– **recommends** that laboratories do not change their value for this quotient until the new value comes into effect,

– **believes** that the value to be adopted will be sufficiently accurate, in terms of SI, that no further change will be required in the foreseeable future.

The unsatisfactory state of volt transfer standards led the CCE also to develop Recommendation E 1 (1986), the thrust of which is that the national standards laboratories "actively pursue the study and improvement of transportable standards with which the volt may be transferred from one laboratory to another . . . " Both Declaration E 1 (1986) and Recommendation E 1 (1986) were subsequently approved by the CIPM at its October 1986 meeting [14].

2.2 Quantum Hall Effect

The principal quantum Hall effect (QHE) topics reviewed in detail by the CCE were [12] (i) the values and accuracies achieved in measurements of the quantized Hall resistance $R_H = h/e^2$ in terms of national representations of the ohm; (ii) the values of R_H in SI units and their uncertainties obtained by direct calculable capacitor-based measurements and indirectly from fundamental constant determinations; (iii) the prospects for future SI values of R_H with their expected uncertainties and dates of availability; (iv) the results of recent comparisons of national units of resistance using transportable resistance standards; (v) the agreement among the present values of R_H in laboratory units and the agreement between various realizations of the SI ohm based on the calculable capacitor; (vi) the precautions required to ensure reliable results from a quantized Hall resistance sample and the availability of good samples; and (vii) the need for further intercomparisons of national units of resistance.

With regard to (i), most laboratories were able to determine R_H in terms of their national ohm with an uncertainty in the range 0.02 to 0.1 ppm. Under (ii) and (iii), the uncertainties of the values of R_H in SI units, both direct and indirect, varied between 0.020 to 0.32 ppm, and most values agreed with the value having the smallest uncertainty within 0.2 ppm. A number of new and possibly more accurate results could be expected within two years. With regard to (iv), a 0.05 ppm transfer uncertainty or even better can apparently be achieved if the transport resistors are carefully selected and used. Under (v), the CCE concluded that most measurements of R_H in laboratory units agreed within an uncertainty of 0.2 ppm but that the agreement among realizations of the SI ohm was somewhat worse. With regard to (vi), the CCE decided that while tests were available which could be used to ensure reliable results from a particular quantized Hall resistance sample, and that a number of good samples are already in hand, increased understanding of the QHE as well as additional metrologically useful samples were highly desirable. Finally, under (vii), the CCE decided that it would be useful to conduct an international comparison of 1-Ω resistance standards to facilitate the comparison of measurements of R_H in laboratory units.

The result of the CCE's review of these quantum Hall effect topics was the following formal declaration:

Declaration E 2 (1986)

Concerning the quantum Hall effect for maintaining a representation of the ohm.

The Comité Consultatif d'Electricité

recognizes

– that as an organ of the Convention du Mètre one of its responsibilities is to ensure the propagation and improvement of the SI, the unit system in use throughout the world,

– that worldwide uniformity and constancy over a long period of time of national representations of the ohm are of great technical and economic importance to commerce and industry,

– that the application of the quantum Hall effect as a means of maintaining a stable representation of the ohm is being developed rapidly in many national standards laboratories,

– that the quantum Hall effect is providing very reproducible results from one laboratory to another, but that the number of usable samples available is insufficient for present needs,

– that experience is leading to tests that provide assurance of both reproducible and accurate results from a selected sample,

– that no laboratory has yet adopted a value of the quantized Hall resistance R_H to maintain its laboratory representation of the ohm,

– that various laboratories have determined R_H in SI units using both the calculable capacitor and determinations of fundamental constants,

– that additional results for R_H in SI units are

expected to become available in the near future,

is of the opinion

– that the same value of R_H should be adopted simultaneously by all those laboratories that decide to use the quantized Hall resistance as their representation of the ohm,

– that this value should be consistent with SI,

– that such a value can soon be adopted,

in consequence, the CCE

– **establishes** a Working Group charged with making a proposal to the CCE for a value of R_H to be based upon all relevant data that become available up unitl June 15, 1988 and with developing detailed guidelines for the proper use of the quantum Hall effect to maintain a representation of the ohm,

– **decides** to meet in September 1988 with a view to recommending the value of R_H to come into effect on January 1, 1990,

– **gives** notice that the adoption of this value for R_H may lead to a change in national and the BIPM representations of the ohm; this change should in general not exceed 2 parts in 10^6,

furthermore, the CCE

– **recommends** that national laboratories

- vigorously pursue their work to understand better the quantum Hall effect,
- encourage the increased availability and distribution of good quantum Hall effect samples,
- determine the value of R_H in SI units both by the direct realization of the ohm and the determination of appropriate fundamental constants,
- carry out bilateral comparisons as seem appropriate, and communicate without delay all their results to the Working Group,

– **recommends** that the BIPM organize during 1987/88 an international comparison of one ohm resistance standards in connection with the quantum-Hall effect work,

– **recommends** that no laboratory should adopt a value of R_H for its representation of the ohm or use the quantum Hall effect to alter the present drift rate until the recommended value comes into effect,

– **believes** that the value to be recommended in 1988 will be sufficiently accurate, in terms of SI, for no change to be required in the foreseeable future.

The less than satisfactory current state of understanding of the QHE and the limited availability of good samples led the CCE also to develop Recommendation E 2 (1986) which encourages (a) studies of QHE sample manufacture and characterization, (b) the provision of an adequate supply of high quality QHE devices for metrological purposes by industry and research laboratories, (c) better theoretical and experimental understanding of the QHE, and (d) comparisons of QHE devices under the auspices of the BIPM. Both Declaration E 2 (1986) and Recommendation E 2 (1986) were also subsequently approved by the CIPM at its October 1986 meeting [14].

3. Conclusion

If all proceeds as planned, that is, if the several new values for $2e/h$ and R_H in SI units which are expected to become available by June 15, 1988, agree with earlier results within acceptable limits, then the CCE at its 18th Session in September 1988 will officially recommend for adoption a new value for the Josephson frequency-voltage ratio $2e/h$ consistent with the SI, and a value of the quantized Hall resistance $R_H = h/e^2$ also consistent with the SI, to be used by all national standards laboratories and the BIPM to define and maintain their representations of the volt and ohm. These new values, which would be implemented simultaneously throughout the world starting January 1, 1990, are anticipated to have an uncertainty of between 0.1 and 0.3 ppm. Moreover, the uncertainty associated with using the Josephson and quantum Hall effects to define and maintain representations of the volt and ohm should generally be in the range 0.01 to 0.1 ppm. As a consequence, starting January 1, 1990, the practical electrical units for voltage, resistance, and current of most industrialized countries will be equivalent within an uncertainty no greater than about 0.1 ppm and these units will be consistent with their respective SI units within an uncertainty no greater than about 0.3 ppm. Although implementing these new representations will require adjusting a large industrial inventory of standards and instruments by significant amounts (e.g., in the United States the U.S. Legal Volt will increase about 9 ppm and the U.S. Legal Ohm about 1.5 ppm), the benefits of international uniformity of electrical measurements and their consistency with the SI which will result from the unit changes should completely outweigh the costs of making them.

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History of the Present Value of $2e/h$ Commonly Used for Defining National Units of Voltage and Possible Changes in National Units of Voltage and Resistance

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Abstract—The national standards laboratories of most major industrialized countries employ the Josephson effect to define and maintain their national or laboratory unit of voltage V_{LAB}. The value of the Josephson frequency-voltage ratio commonly used for this purpose, $2e/h \equiv 483\,594$ GHz/V_{LAB}, is now known to be about 8 ppm less than the absolute or International System of Units (SI) value. Consequently, the different national units of voltage are smaller than the SI unit by the same amount. One of the purposes of this paper is to review how this value of $2e/h$ was selected and, hence, the origin of the present inconsistency between national voltage units and the SI unit. The motivation for such an historical study is the hope that it can benefit the selection of a new, more accurate value of $2e/h$ planned for the near future. Also discussed is the status of national units of resistance and the effect of defining and maintaining such units using a value of the quantized Hall resistance consistent with the SI, as may be suggested in the near future as well.

I. Introduction

THE SYSTEM of units in general use to express the results of physical measurements is the International System of Units (SI). Because the SI definitions of the volt (V) and ohm (Ω) are difficult to realize with high accuracy, national standards laboratories such as the U.S. National Bureau of Standards (NBS) have historically used practical representations of them to serve as the national or legal electrical units. For example, the mean EMF of a particular group of electrochemical standard cells of the Weston type (each with an EMF of order 1.018 V) has traditionally been used to define a laboratory or as-maintained national unit of voltage V_{LAB}, and the mean resistance of a particular group of precision wire-wound resistors of the Thomas or similar type (each with a resistance of order 1 Ω) has similarly been used to define a laboratory or as-maintained national unit of resistance Ω_{LAB}. The national unit of current A_{LAB} is then defined in terms of V_{LAB} and Ω_{LAB} by means of Ohm's law, $A_{LAB} = V_{LAB}/\Omega_{LAB}$, and does not require its own separate representation.

The national standards laboratories of most major industrialized countries now use the Josephson effect [1] to define their unit of voltage and maintain it constant in time. A low-temperature solid-state physics phenomenon, the Josephson effect occurs when two superconductors separated by 1–2 nm (achievable with an oxide layer) are cooled below their transition temperatures. If such a Josephson junction is exposed to microwave radiation of frequency f, current steps appear in its current–voltage curve at quantized values of voltage. The voltage V_n of the nth step and the frequency f are related by $2eV_n = nhf$ where e is the elementary charge and h is the Planck constant. A Josephson junction can thus be viewed as a perfect frequency-to-voltage converter with the constant of proportionality being the invariant fundamental–constant ratio $2e/h$. Because frequencies can be readily measured to very high accuracy, the Josephson effect can be used to define and maintain V_{LAB} to an accuracy limited only by the uncertainty with which the voltage across the Josephson device can be compared with the 1.018-V EMF of a standard cell. Typically this is in the range 0.01–0.1 ppm.[1] The standard cell now serves only as a "flywheel," that is, as a means of preserving or storing V_{LAB} between Josephson effect measurements.

II. Origin of CCE Recommended Value of $2e/h$

The value of $2e/h$ in widest use for volt-maintenance purposes

$$(2e/h)_{CCE} \equiv 483\,594.000 \text{ GHz}/V_{LAB} \qquad (1)$$

is based on a 1972 recommendation of the Consultative Committee on Electricity (CCE) of the International Committee of Weights and Measures (CIPM). The recommendation, officially known as Statement E-72, was developed at the thirteenth session of the CCE held in October 1972 [2], [3]. Subsequently approved by the CIPM at its sixty-first session [4] (also held in October 1972), and reiterated in 1975 by both the CCE [5], [6] and CIPM [7], it reads:

Statement E-72

The Consultative Committee on Electricity
Considering
that the Josephson effect enables potential steps to be reproduced with a high precision,

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IEEE Log Number 8613596.

[1]Throughout, all uncertainties are one standard deviation estimates unless otherwise noted.

that several laboratories are using this device in order to maintain their realizations of the volt at a constant value; and

that their results make it possible to relate the value of the potential steps of the Josephson effect to the realizations of the volt maintained in several laboratories,

Considers from these results that, on January 1, 1969, $V_{69\text{-BI}}$ was equal within half a part per million to the potential step which would be produced by a Josephson junction irradiated at a frequency of 483 594.0 GHz.

Here, $V_{69\text{-BI}}$ is the as-maintained or laboratory unit of voltage of the International Bureau of Weights and Measures (BIPM) defined starting January 1, 1969 in terms of a group of standard cells.[2] Since the EMF's of chemical cells vary with time, $V_{69\text{-BI}}$ is expected to be a time-dependent unit.[3] Whether the 0.5-ppm uncertainty of Statement E-72 was meant to correspond to a one-, two-, or three-standard deviation estimate, or something else, was never explicitly indicated by the CCE. The countries that use the CCE value of $2e/h$ include Australia, Canada, Germany, Finland, Italy, Japan, the Netherlands, and the U.K.

The value of $2e/h$ in terms of $V_{69\text{-BI}}$(January 1, 1969) given in Statement E-72 was derived by J. J. Denton [10] of the National Physical Laboratory (NPL), U.K. Denton's analysis was based on a linear extrapolation of $2e/h$ measurements carried out in Australia, Germany, the U.K., and the U.S. from 1969 to 1972. The measurements were made in terms of the time-dependent laboratory units of these respective countries as defined by means of electrochemical cells and the extrapolated values were converted to values expressed in terms of $V_{69\text{-BI}}$(January 1, 1969). This conversion was based on the differences V_{LAB}(January 1, 1969) $-$ $V_{69\text{-BI}}$ calculated from the results of the 1967 and 1970 triennial international comparisons of national units of voltage (and resistance) carried out using transportable cells (and resistors) at the BIPM.

Denton's calculation and thus CCE Statement E-72 was subsequently confirmed by a more rigorous but similar analysis based on linear least squares fits carried out by E. R. Cohen and the author in conjunction with the 1973 least squares adjustment of the fundamental constants [11]. The analysis, which included additional $2e/h$ measurements and volt unit intercomparison data which had subsequently become available, indicated that $V_{69\text{-BI}}$(January 1, 1969) corresponded to a Josephson frequency of 483 593.987(90) GHz (0.19 ppm). Cohen and the author have recently extended this analysis in conjunction with the 1986 least squares adjustment [12]. Taking into account the added results of the 1973 triennial international comparison and 41 $2e/h$ measurements carried out at BIPM in terms of $V_{69\text{-BI}}$ over the period of October 1974 to July 1976, we obtain 483 593.876(48) GHz (0.10 ppm). One may thus conclude that Statement E-72 is correct since the value it recommends is only 0.26 ppm larger than this last and, presumably, highly reliable value.

III. Consistency of $(2e/h)_{CCE}$ with the SI, Other Values in Use, and Implications

The CCE based its Statement E-72 on $V_{69\text{-BI}}$(January 1, 1969) because it believed that this unit was highly consistent with the SI unit. In other words, the CCE recommended value of $2e/h$ was expected to be very nearly equal to the SI value and, hence, any laboratory voltage unit based on it was expected to be highly consistent with the SI. Unfortunately, this has not turned out to be the case. As long ago as 1976 the author pointed out the likelihood of $(2e/h)_{CCE}$ being from 4 to 10 ppm smaller than the SI value [13]. Since then, force balance and similar direct realizations of the SI volt [14], [15] as well as determinations of relevant fundamental physical constants [16] have advanced to the point that one can now state that the SI value of $2e/h$ exceeds that suggested by the CCE by about 8 ppm with an uncertainty of less than 0.5 ppm. As a consequence, the national unit of voltage of each country that employs the Josephson effect and $(2e/h)_{CCE}$ is smaller than the SI unit by about 8 ppm.

The inconsistency between V_{LAB} and V means that electrical and mechanical measurements of force, energy, and power will not yield the same results. Perhaps even more significant, three countries currently use values of $2e/h$, which *differ* from $(2e/h)_{CCE}$. The Central Laboratory of the Electrical Industries (LCIE), France, employs [17]

$$(2e/h)_{LCIE} \equiv 483\ 594.64\ \text{GHz}/V_{LCIE} \tag{2}$$

the U.S. NBS uses [17]

$$(2e/h)_{NBS} \equiv 483\ 593.420\ \text{GHz}/V_{NBS} \tag{3}$$

and the All-Union Scientific Research Institute of Metrology (or Mendeleyev Institute of Metrology (IMM)), USSR, employs [18]

$$(2e/h)_{IMM} \equiv 483\ 596.176\ \text{GHz}/V_{IMM}. \tag{4}$$

The French value was chosen to prevent a discontinuity in the French volt when converting from standard cells to the Josephson effect as the basis for V_{LCIE} in the early 1970's. The U.S. value was chosen for the same reason. The USSR value was selected in the late 1970's to make V_{IMM} more consistent with the SI unit and is based on an IMM analysis of the results of certain fundamental constants experiments then available.

The consequences of (2)–(4) are as follows: the French volt is 1.32 ppm *larger* than the volt of those countries which use $(2e/h)_{CCE}$ and about 6.7 ppm smaller than the SI volt; the U.S. volt is 1.20 ppm *smaller* than the volt of these same countries and about 9.2 ppm smaller than the SI unit; and the USSR volt is 4.50 ppm *larger* than

[2] The BIPM is located in a suburb of Paris, France and is the "international" standards laboratory. Established by the Treaty of the Meter signed in Paris May 20, 1875, its principal function is to ensure worldwide uniformity of physical measurements.

[3] It was therefore supplanted on January 1, 1976 by the time-independent unit $V_{76\text{-BI}}$ based on the Josephson effect and the CCE value of $2e/h$ [8], [9].

the volt of those countries which use $(2e/h)_{CCE}$ and about about 3.5 ppm smaller than the SI volt.

The chaotic situation regarding national units of voltage as outlined in this section had led the CCE to plan to meet in September 1986 with the aim of reviewing all relevant experiments and, if justified, adopting a new value of $2e/h$ consistent with the SI to be used by *every* national standards laboratory (and BIPM) that employs the Josephson effect to define and maintain its laboratory unit of voltage [19], [20]. In view of this possibility, we examine further the origin of the inconsistency between $(2e/h)_{CCE}$ and the SI value in the hope that such an analysis can benefit the selection process.

IV. Origin of $V_{69\text{-}BI}$(January 1, 1969)

Since it was shown in Section II that statement E-72 is correct, the discrepancy between $(2e/h)_{CCE}$ and the SI value must arise from the unit $V_{69\text{-}BI}$(January 1, 1969). This unit was created by adjusting the unit V_{BIPM} downward by 11 ppm, where V_{BIPM} is the (time-dependent) BIPM as-maintained volt prior to January 1, 1969 based on a group of standard cells. In actual fact, since V_{BIPM} and $V_{69\text{-}BI}$ were based on the same group of cells, their only difference is the 11-ppm redefinition. Formally, on January 1, 1969

$$\begin{aligned} 1\ V_{69\text{-}BI} &= 1 \times (1 - 11 \times 10^{-6})\ V_{BIPM} \\ &= 0.999\,989\ V_{BIPM}. \end{aligned} \tag{5}$$

The observant reader will note that the 8-ppm difference discussed in Section II between $(2e/h)_{SI}$ and $(2e/h)_{CCE}$ implies that on January 1, 1969 V_{BIPM} was 3 ppm larger than the SI volt. Thus if the BIPM volt had not been redefined on January 1, 1969 the CCE would have recommended a value of $2e/h$, only 3 ppm larger than $(2e/h)_{SI}$, rather than the current value which is 8 ppm smaller than $(2e/h)_{SI}$.

The 11-ppm adjustment of V_{BIPM} on January 1, 1969 was intended to bring the BIPM volt into agreement with the SI unit. The CCE authorized the adjustment through Recommendation E-1 developed at its twelfth session held in October 1968 [21], [22]. Subsequently approved by the CIPM at its fifty-seventh session (also held October 1968) [23], it reads:

> Recommendation E-1
>
> The Consultative Committee on Electricity
> *Considering*
> that the resistance and electromotive force standards of the BIPM have defined since January 1, 1948 the reference values Ω_{BIPM} and V_{BIPM} to which are referred similar values defined by the standards of the national laboratories;
> that the BIPM considers that the time has come to bring Ω_{BIPM} and V_{BIPM} into better agreement with the ohm and the volt obtained by absolute determinations,
> *Recommends* that the Bureau International should be authorized to use the following new reference values starting from January 1, 1969:
>
> $$\Omega_{69\text{-}BI} = \Omega_{BIPM}$$
> $$V_{69\text{-}BI} = V_{BIPM}(1 - 11 \times 10^{-6}).$$
>
> The Consultative Committee on Electricity notes that the national laboratories consulted during the meeting are ready to adjust the values of their standards at the same date or soon afterwards, and it established that these adjustments would ensure a better uniformity of measurements throughout the world, together with a better agreement with the SI definitions of the electrical units.

As indicated in the last sentence of Recommendation E-1, most national standards laboratories also adjusted their national unit of voltage[4] (resistance) on January 1, 1969 in order to bring it into agreement with $V_{69\text{-}BI}$(January 1, 1969) ($\Omega_{69\text{-}BI}$(January 1, 1969)). The size of the adjustment was determined by the difference between V_{LAB} and V_{BIPM} (Ω_{LAB} and Ω_{BIPM}) obtained in the 1967 triennial international comparison of national units of voltage (resistance). For example, on January 1, 1969 the NBS unit of voltage V_{NBS} was *decreased* by 8.4 ppm. This should be compared with the 9.2 ppm by which V_{NBS} as defined by (3) must now be *increased* to bring it into agreement with the SI volt.

It is important to recognize that Recommendation E-1 does not give the uncertainty to be associated with $V_{69\text{-}BI}$(January 1, 1969) relative to the SI unit. That is, there is no indication of how well $V_{69\text{-}BI}$(January 1, 1969) represents the SI volt. Indeed, to take an extreme example, if the uncertainty to be assigned the 11-ppm correction were itself 11 ppm, it would be difficult to justify the change. It is, therefore, important to examine how the 11 ppm came about, and its uncertainty.

The 11-ppm correction was apparently first suggested by J. Terrien, then BIPM Director, at the eleventh session of the CCE held in October 1965 [25], [26]. The details of his analysis were given in a paper presented at the 1966 Conference on Precision Electromagnetic Measurements and subsequently published in the conference proceedings [27]. Based on the 1956 NBS current balance realization of the ampere, a similar 1962–1963 NPL determination, the results of the 1964 triennial international comparison of national units of voltage and resistance, and five realizations of the SI definition of the ohm carried out by five national laboratories from 1957 to 1964 using several different methods, Terrien concluded that

$$1\ \Omega_{BIPM} = 1.000\,000\ \Omega \tag{6}$$

with an uncertainty which might be about 1 or 2 $\mu\Omega$; and that

$$1\ V_{BIPM} = 1.000\,011\ V \tag{7}$$

with an uncertainty of about 3 or 4 μV. Although it was not made clear just what the 3- or 4-μV or ppm uncertainty associated with (7) meant, it was most likely a probable error (PE) or 50-percent confidence level estimate since this was the approach used in the NBS and NPL ampere experiments [28]. Assuming normally distributed data, the one standard deviation uncertainty estimate would then be 4.5–6 ppm (i.e., 1 standard devia-

[4]It should be noted that prior to 1972, all national units of voltage were based on electrochemical cells.

tion = 1.48 × PE [28]). The values obtained from the two separate experiments were given as 1 V_{BIPM} = 1.0 000 140 V and 1 V_{BIPM} = 1.0 000 084 V, respectively.

In preparation for the October 1968 CCE meeting, a number of documents were submitted to the Committee which bore on the question of the relationship between Ω_{BIPM} and Ω, and V_{BIPM} and V. In Document CCE/68-9, the National Standards Laboratory of Australia (NSL), now known as the National Measurement Laboratory (NML) of the CSIRO Division of Applied Physics, reported additional results from their calculable-capacitor realization of the SI ohm which showed that on February 12, 1967, the mean date of the 1967 triennial international comparison of national units of voltage and resistance, 1 $\Omega_{BIPM} = 1\ \Omega - (0.2 \pm 0.7)\ \mu\Omega$. This result was generally taken as confirmation of the equality of Ω_{BIPM} and Ω, implying that the difference between the BIPM ampere and the SI ampere was essentially the same as the difference between the BIPM volt and the SI volt.

In Document CCE/68-11, NBS deduced the value

$$1\ V_{BIPM} = 1\ V + 11.0\ \mu V \tag{8}$$

based mainly on the following: 1) a slightly revised value for the result of their 1956 current balance experiment (the change was due to improved knowledge of the gravitational acceleration); 2) a 1967 SI ampere realization using an improved version of the NBS Pellat torque balance; 3) a slightly revised value for the result of the 1962–1963 NPL current balance experiment; and 4) a realization of the ampere derived from the NBS and NPL determinations of the proton gyromagnetic ratio by the low-field method and the Kharkov State Institute of Measures and Measuring Instruments (USSR) determination of the same quantity by the high-field method [28].

In Document CCE/68-34, IMM derived the result

$$1\ V_{BIPM} = 1\ V + 11.2\ \mu V \tag{9}$$

in a manner essentially identical to that of NBS but also included low-field proton gyromagnetic ratio measurements from Japan and the USSR [28].

The 11-ppm correction to V_{BIPM} first suggested in 1965 by Terrien was thus confirmed by the results and analyses given in these three documents, and the basis for putting forward Recommendation E-1, apparently firmly established. However, it must be emphasized that *neither Document CCE/68-11 nor Document CCE/68-34 included any estimate of the uncertainty to be associated with their deduced values* (i.e., with (8) and (9)). This uncertainty would have had to been in the 3–4-ppm range based on the *a priori* uncertainties of the several experiments involved.[5] One wor.ders whether the following critical question was ever asked: is the uncertainty in the proposed 11-ppm correction to V_{BIPM} sufficiently small to justify making it? Perhaps if greater attention had been paid in these two documents to calculating the uncertainty to be associated with the correction, the CCE would have recognized that the latter was only three to four times larger than the former and concluded that even though the various measurements agreed, in view of this small "margin of safety," the best approach would be to do nothing until more accurate results were available. As it now stands, the thousands of laboratory and industrial voltage standards and related instruments throughout the world which have a precision of say 25 ppm or better will no doubt eventually have to be readjusted.

[5]A rigorous treatment of these and additional experiments carried out by the author and his coworkers in 1969 within the framework of a least squares adjustment of the fundamental constants [28] yielded 1 $V_{69\text{-}BI} = 1 \times [1 - (11.4 \pm 2.6) \times 10^{-6}]\ V_{BIPM}$ on January 1, 1969.

V. Laboratory Units of Resistance and the Quantum Hall Effect

The mean resistance of a particular group of precision wire-wound resistors is still the means by which most national standards laboratories define their laboratory unit of resistance. However, starting in 1963 the NML in Australia has had in continuous operation a calculable capacitor-based apparatus which has been used to realize periodically the SI definition of the ohm and determine the relationship between Ω_{NML} and Ω [29]. Indeed, starting in 1969, the NML has defined their laboratory unit in terms of their realization of the SI ohm and maintained Ω_{NML} equal to Ω with an uncertainty on the order of 0.1 ppm.

Through the official BIPM triennial international comparisons of national units of resistance using transportable reference resistors and similar official comparisons involving a limited number of countries, it is possible to determine the drift rate and value relative to the SI of the national unit of resistance of most industrialized countries based on the NML calculable capacitor measurements. For example, a recent analysis by E. R. Cohen and the author in connection with the 1986 least squares adjustment of the constants [12] indicates that Ω_{BIPM} is changing at a rate of $-(0.0\ 566 \pm 0.0\ 015)$ ppm/per year and that on January 1, 1985, 1 $\Omega_{BIPM} = 1\ \Omega - (1.46 \pm 0.14)\ \mu\Omega$. For NBS the respective figures are $-(0.0\ 589 \pm 0.0\ 065)$ and $-(1.23 \pm 0.15)$, while for the National Research Council (NRC) of Canada, $-(0.150 \pm 0.060)$ and $-(3.37 \pm 0.16)$. Similar values are obtained for other laboratories.

Although a number of other countries now have, or shortly will have, fully operational calculable capacitor SI ohm realization experiments, it still remains a complex undertaking. (The fact that only one laboratory in the world has had such an apparatus in continuous operation since the method was developed in the early 1960's attests to its difficulty.) Thus metrologists heartily welcomed the discovery in 1980 of the quantum Hall effect (QHE) since the QHE promises to do for resistance-unit definition and maintenance what the Josephson effect has done for voltage-unit definition and maintenance [30], [31].

Like the Josephson effect, the QHE is a low-temperature solid-state physics phenomenon. However, the materials involved are semiconductors rather than supercon-

ductors. The QHE is characteristic of a two-dimensional electron gas (2DEG) realized, for example, in classic Hall-bar geometry, high-mobility semiconductor devices such as silicon MOSFET's and $GaAs$–$Al_xGa_{1-x}As$ heterostructures when the devices are placed in a magnetic field of order 10 T and cooled to a few kelvin. Under these conditions the 2DEG is completely quantized and there are regions in the curve of Hall voltage versus gate voltage for a MOSFET, or Hall voltage versus magnetic field for a heterostructure, where the Hall voltage remains constant as the gate voltage or magnetic field is varied.[6]

On these so-called Hall plateaus the Hall resistance $R_H(i)$, defined as the ratio of the Hall voltage of the ith plateau $V_H(i)$ to the current I through the device, $R_H(i) = V_H(i)/I$, is quantized and given by $R_H(i) = h/(e^2 i)$ with the quantum integer i equal to the plateau number. Numerically, $h/e^2 \approx 25\,812.8\ \Omega$ and, hence, the resistance of the readily obtainable $i = 4$ plateau is $\approx 6453.2\ \Omega$. A QHE device can thus be viewed as a resistor whose resistance depends only on the fundamental-constant ratio h/e^2. As such it can be used to define and maintain Ω_{LAB} to an accuracy limited only by the uncertainty with which the resistance of the device (when on a plateau) can be compared with the 1-Ω resistance of a standard resistor. Eventually this is expected to be in the range 0.01–0.1 ppm for all laboratories. In analogy with the standard cell and the Josephson effect, the standard resistor would serve only to store Ω_{LAB} between QHE measurements.

The quantized Hall resistance $R_H \equiv h/e^2$ is related to the fine-structure constant α, the dimensionless expansion parameter of quantum electrodynamic (QED) theory, by $R_H = \mu_0 c/2\alpha$. Here $\mu_0 \equiv 4\pi \times 10^{-7}$ H/m is the magnetic permeability of vacuum and $c \equiv 299\,792\,458$ m/s is the speed of light in vacuum. Thus since μ_0 and c are exactly defined constants, if α is known from some QED-related experiment with a given uncertainty, R_H will be known in SI units with the same uncertainty. An alternate method of determining R_H is to measure a Hall resistance $R_H(i)$ in terms of Ω_{LAB}, which in turn is measured in terms of the SI ohm by means of a calculable capacitor.

Most of the major national standards laboratories as well as the BIPM are currently putting into place the apparatus necessary to define and maintain their unit of resistance using the QHE. Thus the CCE also plans to review all relevant experiments at its September 1986 meeting and if justified, adopt a value of $R_H \equiv h/e^2$ consistent with the SI to be used by *every* national standards laboratory (and BIPM) that chooses to employ the QHE to define and maintain its laboratory unit of resistance [19], [20]. Since for most countries Ω_{LAB} differs from the SI unit by only a few tenths to 2 ppm, and the number of laboratory and industrial resistance standards and related instruments of this level of precision is limited, the changeover to the QHE should have a milder impact than the adoption of a new value of $2e/h$.

[6]The magnetic field is applied normal to the 2DEG, which is in the plane of the device; a current is passed along the length of the device normal to the field and carried by the 2DEG; and the Hall voltage is measured in the direction normal to the current across the width of the device.

VI. Conclusion

Adopting a new value for the Josephson frequency-voltage ratio $2e/h$ and a value for the quantized Hall resistance $R_H \equiv h/e^2$, both consistent with the SI and both universally accepted and used to define national units of voltage and resistance, would clearly represent a major advance for the international compatibility of electrical measurements and their conformity with the internationally accepted system of units, the SI. However, the lesson of what happened in 1968, when V_{BIPM} was changed by 11 ppm, and the principal point of this paper is clear: no recommendations regarding values of $2e/h$ and R_H should be made unless the data and their uncertainties warrant it, and these uncertainties must be evaluated with great care and objectivity. Indeed, because changing the as-maintained electrical units will have an enormous impact on our technology-dependent industrialized society, one might argue that no decisions should be made until the uncertainties for both $2e/h$ and R_H are conservatively estimated to be at the 0.1–0.2-ppm level. This would effectively guarantee that no further changes would be necessary for many decades, if at all. See [32] for a summary of the September 1986 meeting of the CCE.

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This document provides general guidelines and detailed instructions on how to bring laboratory reference standards of voltage and resistance and related instrumentation into conformity with newly established and internationally adopted representations of the volt and ohm. Based on the Josephson and quantum Hall effects, respectively, the new representations are to come into effect worldwide starting on January 1, 1990. Their implementation in the U.S. will result in increases in the values of the national volt and ohm representations maintained at the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards or NBS) of 9.264 parts per million (ppm) and 1.69 ppm, respectively. The resulting increase in the value of the U.S. representation of the ampere will be 7.57 ppm and in the U.S. electrical representation of the watt, 16.84 ppm. Also discussed are the effects on electrical standards of the January 1, 1990, replacement of the International Practical Temperature Scale of 1968 by the International Temperature Scale of 1990, and of the January 1, 1990, approximate 0.14 ppm decrease in the U.S. representation of the farad.

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